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HYGROSCOPIC PROPERTIES OF CORNCOBS AND THEIR APPLICATION FOR SMALL SCALE ON-FARM GRAIN CONDITIONING

by

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NOMENCLATURE

bu: Bushel (1.25 cubic feet).

Btu: British thermal unit.

°C: Degrees centigrade.

cfm: Cubic feet per minute.

d.b.: Dry basis.

e: Base of the natural logarithm. (2.71828).

exp: Exponential. Indicates that subsequent number is a power of e.

°F: Degrees Farenheit.

gm: Gram.

Hg: Mercury.

H_2O: Water.

Kcal: Kilocalories.

Kg: Kilogram.

lb: Pound.

ln: Natural logarithm.

M_e: Equilibrium moisture content. % d.b.

M_o: Initial moisture content. % d.b.

M_t: Moisture content at any time t. % d.b.

M.C.: Moisture content.

mm: Millimeters.

mph: Miles per hour.

psi: Pounds per square inch.

ppm: Parts per million.

R: Universal gas constant.

R^2: Percent of variation about the mean that is explained by the statistical model.

RH: Relative Humidity.

rep: Replication.

T: Temperature.

t: Time.

w.b.: Wet basis.

λ: Heat of condensation of water.

ΔF: Change in free energy.

ΔS: Change in entropy.

∞: Infinity.

INTRODUCTION

There is presently a worldwide increasing concern about the future food supply. With over 4 billion people and rising population rates, it is clear that in order to meet the world's food demand progress has to be made not only in the areas of production and marketing, but also in storage of food commodities.

No accurate data acutally exist on the amount of annual grain losses that take place from the time that grain is harvested until it reaches its final market destination. Figures higher than 30 percent have been reported for some of the less developed countries (Hall, 1970). Although some of the losses occur in the field or during harvesting, transportation, and marketing, the losses that take place during storage of food grains cannot be neglected.

Storage losses are mainly due to fungi, bacteria, insects, and rodents. Fungi and bacteria growth are also functions of the humidity and temperature of the storage system, as well as the grain moisture content. It is very difficult to store grain in humid climates because the temperature and humidity of the air are high throughout the year.

All hygroscopic materials, like grain, gain moisture when the water vapor pressure of the surrounding air is higher than the vapor pressure of water in the grain. Moisture transfer of this type is called adsorption.

Grain aeration or the passage of a low air volume through

the stored grain for grain conditioning purposes is, therefore, impractical in humid environments.

An artificial grain drying system usually utilizes a method of preheating ambient air to reduce its relative humidity and provide the necessary drying potential. A practical and economical method to store grain for relatively long periods of time in humid environments has not been successfully developed so far for developing countries, especially at the small scale on-farm level.

Some attempts have been made to utilize an adsorbent such as silica gel inside or near the grain mass, in order to reduce the relative humidity of the air and create a more favorable condition for grain quality preservation [Fleske, (1973), and Hsiao, (1974)]. Nevertheless, such adsorbents are expensive, might not be easily available at the farm level, and some complications can arise when it is time to regenerate the silica gel inside the grain mass.

Corn is presently produced by many farmers in many areas of the world. After the corn is harvested and shelled, corncobs are generally left on the field until they decay, and only a small amount is presently being used as a source of heat, feed, or any other purpose.

Given the hygroscopic nature of corncobs, it is conceivable that they can be used to absorb water vapor from humid environments, providing air with a relative humidity low enough to be effective in a drying and storage system.

Before corncobs can be successfully applied in a grain conditioning system, information on their hygroscopic properties has to be known. Among the most useful pieces of information on hygroscopic properties are isotherms, or curves showing the relationship between the product's moisture content and the surrounding air's relative humidity at equilibrium conditions. The rate at which corncobs can absorb moisture is also an important factor in the design and management of the conditioning system.

Therefore, the objectives of this study are to obtain isotherms for corncobs at various temperatures, to obtain rates of water adsorption by corncobs when placed in humid environments, and to develop a drying-conditioning system to be used in developing countries at the small scale on-farm level.

LITERATURE REVIEW

I. Grain Storage and Conditioning Systems

Storage systems for grain can be classified as: 1) Airtight and underground storage; 2) Bag storage; 3) Storage in piles; and 4) Bulk storage.

Airtight storage can take place in underground pits, as well as in upright or flat containers. The basic principle involves the depletion of oxygen to a level which kills or inactivates insects or microbial activity. Oxygen-free atmospheres may result from the respiration of organisms themselves, or can be produced artificially. Most species of insects are killed when the oxygen concentration decreases to about 2% of the intergranular air volume (Bailey, 1965), but fungi can still live in atmospheres with very low oxygen concentrations, down to about 0.2% (Peterson et al., 1956). Although insects and fungi may be killed by such low levels of oxygen, acidity from anaerobic respiration may still develop. Whether the system is under or above-ground, stringent requirements for airtightness must be met in order to provide satisfactory storage without quality deterioration.

Grain has been stored in underground pits since ancient times. Although not necessarily airtight, some ancient pits were surrounded by straw or similar materials that would absorb moisture entering from the soil or cover. Underground pits are suitable for short or long-term storage as long as moisture is

prevented from entering the pit, and the grain moisture content is sufficiently low. Being in contact with the soil, underground pits ensure a lower temperature than that which prevails in an above-ground structure (Hyde, 1958).

Grain is commonly piled up in jute bags in developing countries, especially at the small scale on-farm level. Protective boards to isolate the bags from direct contact with the ground reduce heating of the bottom of the pile and prevent moisture transfer from the ground. Long-term storage in jute bags without adequate protection from the weather is not a recommended practice. When storing bagged grain in warehouses it is necessary that they offer protection against insects and rodents, and the grain should be kept dry and fumigated properly. Piles of grain stored in warehouses should be kept away from the walls and ceiling. It is important to keep in mind that if the warehouse is located in a humid climate, grain is likely to regain moisture.

Successful storage of bulk grain in piles depends largely on the weather and time of exposure, the characteristics of the ground on which it is piled, the drainage facilities around the edges of the piles, and the care excercised while the grain is piled (Hsiao, 1974). However, storage of bulk grain in piles is not recommended unless for short, temporary periods.

Grain is generally stored in bulk for long periods of time, and keeps well provided it is properly conditioned. Bulk storage can take place in steel, concrete, or wooden silos, as well

as in underground pits, flat storage facilities, cribs, and several types of simple primitive structures. Containers made out of clay or mud and bamboo cribs are widespread in small farms in developing countries.

Proper conditioning before storage involves cleaning and drying. The main purpose in cleaning grain to be stored is to eliminate foreign material that may be the focus of insects and can cause heating of the grain mass. Drying prevents seed germination, and ensures longer quality preservation by decreasing the moisture content of the grain to a level which is not favorable to fungi or bacteria growth.

Grain drying can be classified into natural and artificial drying. Natural drying consists of the use of the sun's rays and atmospheric air to dry the grain. When conditions permit, crops are usually left on the field to mature and dry, but one of the most widespread practices in tropical climates around the world consists of spreading the grain on flat surfaces and turning it occasionally, letting the sun's rays partially reduce the moisture content. Natural ventilation employs atmospheric air to condition the grain when the climate permits. Platforms, cribs, bundles, and other similar structures are used in developing countries for conditioning purposes.

A method which utilizes fans, heaters, mechanical or electrical means of handling the grain and more complicated structures can be thought of as an artificial method of grain conditioning.

Muckle and Stirling (1971) provide an excellent description of the grain drying methods utilized in tropical climates.

Artificial drying systems can be classified into three major groups: low, medium, and high temperature systems.

Attempts have been made to distinguish between very low temperature driers and low temperature driers, but in general the group includes systems which raise the temperature of the ambient air from a few degrees centigrade up to 22 degrees centigrade. Low temperature driers include 1) On-the-floor driers, 2) Flat bed driers, 3) In-bin driers, 4) Sack tunnel driers, and 5) some types of solar driers.

Medium temperature driers include systems which employ drying temperatures of about 32 to 40 degrees centigrade (90 - 105°F), and are utilized where higher moisture extraction rates are required. They include: 1) Batch-in bin and Dryaeration systems, 2) Brook type driers, 3) Tray driers, 4) Radial flow driers, 5) Multiduct grain driers, 6) Sack driers, and 7) certain types of solar driers.

Most high temperature driers operate on a continuous grain flow principle, and are utilized where large volumes of grain are to be dried in a relatively short period of time. They have capacities from 7 to 35 metric tons per hour, and employ drying air temperatures as high as 110 degrees centigrade (230°F), some even higher. Examples of high temperature driers include the familiar vertical elevator drier, and the cascade type drier.

II. Adsorption and Desorption of Water Vapor by Grains

As hygroscopic materials, grains can gain moisture when the water vapor pressure in the surroundings is greater than the water vapor pressure inside them, a process known as adsorption, or they can lose moisture when the water vapor pressure inside them is greater than that of the surroundings, a process known as desorption. Hunt and Pixton (1974) classify water held in grains into three kinds: absorbed, adsorbed, and bound water. The term absorbed water applies when a quantity of water is loosely held inside the grain or in the intergranular spaces by capillary forces. The characteristics of this water are thought to be the same as those of common water, and it is sometimes termed free-water.

Water is said to be adsorbed when it is held in the grain by molecular attraction, being closely related to the adsorbing materials, and being held more firmly. Physically adsorbed water is held in the system by van der Waal's forces.

Bound water or chemically adsorbed water is held in the grain by very strong chemical forces, and it is a chemical union with the adsorbing materials. Large quantities of energy are required to break the chemical bonds, and this bound water usually remains within the system after common drying.

The amount of water that can be adsorbed by grains is studied by means of the isotherm. An isotherm is a curve that describes the amount of water in a substance at a particular

temperature as a function of the equilibrium vapor pressure, water activity, or relative humidity. The equilibrium relative humidity (ERH) is defined as follows:

$$ERH = \frac{\%\ \text{Relative Humidity}}{100} = P/P_o \qquad (1)$$

where P is the vapor pressure exerted by the water in the grain at the given temperature, and P_o is the saturation vapor pressure of water at the same temperature.

Grain can reach equilibrium statically or dynamically, depending on whether there is a flow of air past the grain. For a great number of isotherm determinations cereal grains are allowed to reach equilibrium statically, in containers with different concentrations of sulfuric acid or salt solutions which exert different vapor pressures. In most grain drying systems the material reaches equilibrium dynamically since a flow of air is passed through the grain mass.

Jones (1951) suggested that the dynamic equilibrium is higher than the static equilibrium moisture content. McEwen, Simmonds and Ward (1954) define the dynamic equilibrium moisture content as the asymptotic value of the drying curve. However, no conclusive research has been done on the subject to determine if the static equilibrium moisture content is a good boundary for the design of drying systems, but in general, the dynamic equilibrium moisture content seems to be a little higher.

A. Isotherms

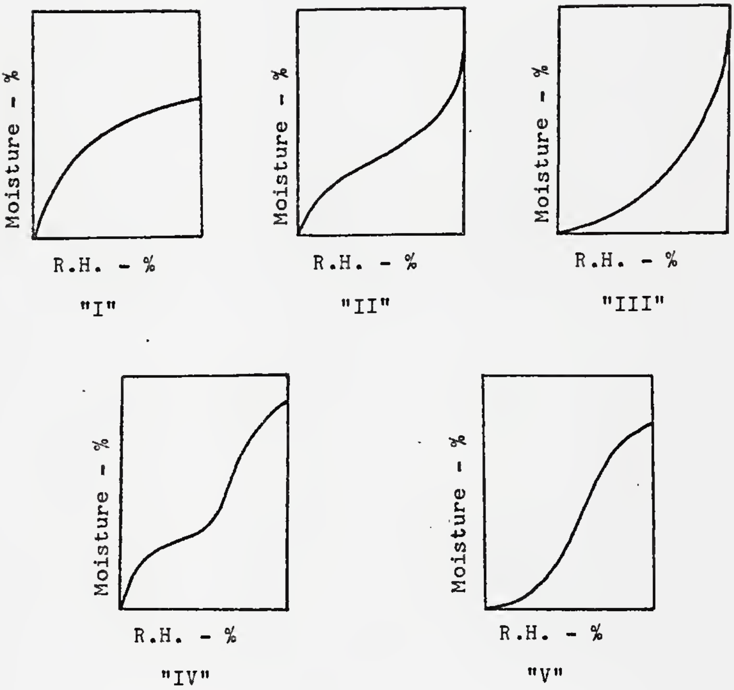
Brunauer (1943) classified adsorption isotherms into five types, as shown in Figure 1.

The Type I curve is known as the Langmuir's adsorption isotherm, or van der Waal's adsorption. Type I isotherm covers monolayer adsorption, and it sometimes describes the initial parts of Type II and IV isotherms.

Type II isotherm is called the S-shaped or sigmoid curve, and it describes the adsorption of water vapor by most cereal grains and their products.

Type III isotherm is related to type II since both cover multimolecular adsorption and they indicate that adsorption increases indefinitely as the vapor pressure P_o is approached. Type IV and V isotherms describe the adsorption on highly porous adsorbents, and the two suggest that the maximum adsorption tends to have a finite value at some point near the saturation vapor pressure of the gas.

Several theories and equations have been developed by a number of investigators to describe adsorption isotherms for grains. One of the most useful and widely tested theories was proposed by Brunauer, Emmett, and Teller (1938), and it is frequently referred to as the B. E. T. theory. According to the B. E. T. theory of multilayer adsorption, the first portion of the sigmoid isotherm represents the adsorption of the first layer of water vapor molecules onto the adsorbent's surface; the region of inflection indicates the deposition of a second layer of water molecules, and the third portion of the isotherm



(R.H.: Relative Humidity)

Figure 1. Types of adsorption isotherms as classified by Brunauer (1943).

represents the continued adsorption of additional layers.

Some modifications to the above theory have been proposed, one of which suggests that the radius of the capillary tubes in the adsorbent determines the amount of additional layers that can be adsorbed at the higher vapor pressures. Detailed explanations of the modifications to the B. E. T. theory can be found in the works of Gregg and Sing (1967) and Labuza (1968).

In each of the 3 segments of the sigmoid isotherm there seems to be a different relationship between the vapor pressure and the equilibrium moisture content. The initial portion appears to be governed by the binding energy between the water molecules and the adsorbent's surface. The binding energy depends on the surface, its chemical composition, and on the physical and chemical properties of water.

In the second and almost linear portion of the isotherm, water molecules are depositing on the already formed monolayer. The energy involved in this process is primarily that of condensation of water, and the amount of adsorption in this range is largely dependent on the water vapor pressure.

In the high humidity range the vapor pressure is determined by the second layer, and addition of a third and other layers seems to depend on the possibility for capillary condensation.

Theimer (1951) suggested that water is not really accumulated in layers but instead it is adsorbed at polar sites as clusters of molecules.

Several investigators have studied the sigmoid-shaped

isotherm and have proposed equations which apply to different ranges of relative humidities.

Henderson (1952) proposed the equation

$$1 - RH = \exp(-cTM_e^{\,n}) \tag{2}$$

for isotherms of different grains, where RH is the relative humidity of the air in decimal, T is the absolute temperature in degrees Rankine, M_e is the equilibrium moisture content in percent dry basis, and n and c are constants for different materials. Thompson (1972) modified Henderson's equation by adding another constant which moves the temperature of absolute zero to a higher temperature.

Chung and Pfost (1967) developed the equation

$$\ln RH = -(A/RT)\exp(-BM_e) \tag{3}$$

where RH is the equilibrium relative humidity in decimal, R is the universal gas constant in Btu/lb.mole-°R, T is the absolute temperature in degrees Rankine, M_e is the equilibrium moisture content in percent dry basis, and A and B are constants. The equation applies remarkably well for corn, for a wide range of relative humidities. (5 to 95%). Pfost et al. (1976) improved the original Chung and Pfost equation by adding another constant to modify the temperature of absolute zero.

Dunstan (1972) prepared a good review of other isotherm theories and equations, including Polanyi's multimolecular

adsorption theory, Hoover's and Mellon's isotherm equation, modifications of the B. E. T. theory, Smith's equation, modifications of Henderson's and Chung's equation, and some empirical equations, among others.

B. Hysteresis

Adsorption and desorption isotherms for grains are both sigmoid shaped but the desorption isotherm generally shows higher equilibrium moisture contents than the adsorption isotherm for the same relative humidities, as illustrated in Figure 2.

Thus, the moisture content of a product can have two values, depending on whether adsorption or desorption is taking place. This phenomenon is called hysteresis. Several investigators have proposed theories to explain the hysteresis phenomenon, but the entire mechanism is not completely understood.

Smith (1947) suggested that hysteresis is due to swelling, which increases the surface area of the adsorbent and has an effect on its structure. Babbitt (1949) inferred that the structure of the adsorbent had a definite effect on hysteresis since it was not as pronounced for wheat flour as for whole wheat.

Pierce and Smith (1950) concluded that hysteresis results from energy changes which take place when water, which is first deposited as clumps at active centers, merges to form a layer

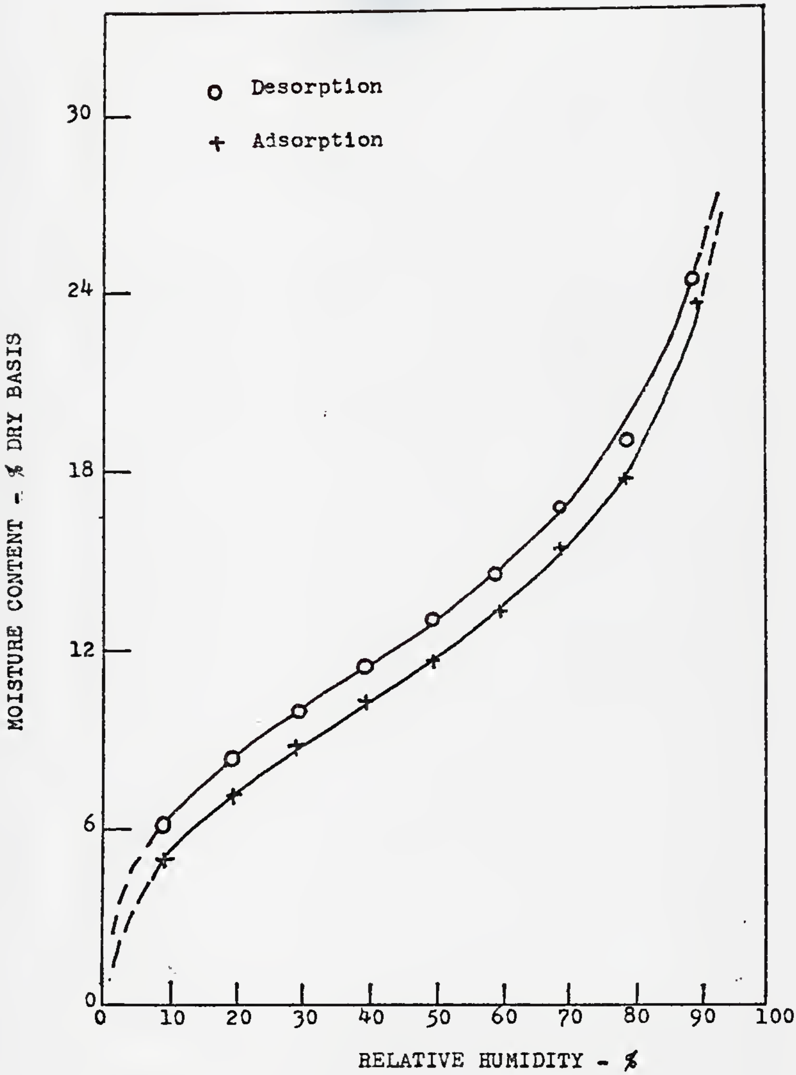


Figure 2. Adsorption-desorption isotherms for corn at 22°C showing hysteresis. Data from Chung (1966).

that covers the adsorbent's surface.

Young and Nelson (1967) hypothesized that water can be held in the adsorbent by three mechanisms: 1) A unimolecular layer of water molecules bound to the surface of the cells, 2) other molecular layers stacked on top of the first, and 3) moisture within the cell of the adsorbent. They suggested that as the amount of water builds up the diffusional forces exceed the binding forces from the surface molecules, allowing some molecules to move into the cell. During desorption all the moisture from the surface has to be removed before there is a force that tends to pull the molecules out of the cell.

Based on their study of the heats of desorption and adsorption, Chung and Pfost (1967) concluded that more sorptive sites are available during desorption than during adsorption, and that the difference causes hysteresis to occur. They stated that if water molecules between adjacent polar groups are removed in high vacuum or at high temperatures, the distance between two polar groups may become so small that a water molecule could not get between them, or two adjacent groups might be held to each other by hydrogen bonds. Since samples are usually dried prior to adsorption experiments, reduced availability of polar sites is expected. On the other hand, Chung and Pfost state that when an adsorbent is wetted, cracks may be formed. If so, an increase in the surface area and availability of sorption sites is expected when an adsorbent is wetted prior to desorption. This explanation is considered an excellent one by other investigators.

Chung and Pfost also found that for wheat the hysteresis effect disappears in the third adsorption-desorption cycle. They suggest that the chemical and physical structure of the adsorbent may finally become so stable that no further molecular shrinkage or crack formation occurs.

Hart (1964) found that as temperature increases, the hysteresis effect decreases. Tuite and Foster (1963) state that artificial drying with temperatures up to 60°C increases the equilibrium relative humidity for corn, and that it should be stored at 0.5 to 1% lower moisture content than naturally dried corn in order to prevent mold development. Ayerst (1965) stated that drying may produce a reverse hysteresis effect on some products.

C. Heat of Adsorption

When a quantity of water is adsorbed on a surface a quantity of heat is given out. This heat is called the heat of adsorption. Likewise, when a quantity of water is desorbed from a surface a quantity of heat is taken up. A measure of the heat of adsorption or desorption indicates the binding energy of the intermolecular forces between water vapor and the surface of the sorbent.

Free energy change is the energy required to transfer water molecules from the vapor state to the solid surface or vice versa. That quantity can be considered as a measure of the work done during the process of adsorption or desorption.

Chung and Pfost (1967) obtained the free energy changes and heats of adsorption and desorption from isotherms for corn and corn products from 4 to 20% moisture content and reported them to range from 10.5 to 16 kcal. per mole, results which are comparable to those of Becker and Sallans (1956), Bushuk and Winkler (1957), and Rodriguez-Arias (1963). The free energy of sorption can be expressed by

$$\Delta F = RT \ln \left(\frac{P}{P_o} \right) \tag{4}$$

where ΔF is the free energy change of sorption, R is a universal gas constant, T is an absolute temperature, P is a partial pressure of the vapor, and P_o is a saturation pressure at T.

A plot of the variation of equilibrium vapor pressure with temperature corresponding to a constant amount of gas adsorbed is an isostere. The Clapeyron-Clausius equation can be written in terms of the heat of adsorption as

$$\left(\frac{\ln P}{(1/T)} \right)_m = \frac{-q_{st}}{R} \tag{5}$$

where m is any constant moisture content, and q_{st} is the isosteric heat of adsorption. A plot of ln P versus 1/T for a constant amount of gas adsorbed should yield a straight line with a slope equal to the isosteric heat of adsorption diveded by R.

The integrated form of equation (5) for a small pressure and temperature range can be used to calculate the isosteric

heat of sorption for different products if isotherms at temperatures T_1 and T_2 are available. The integrated form of equation (5) used by Chung and Pfost (1967), and Becker and Sallans (1956) is

$$H_{st} = R\left(\frac{T_1\ T_2}{T_2 - T_1}\right) \ln\left(\frac{P_2}{P_1}\right) \qquad (6)$$

where P_1 and P_2 are the equilibrium pressures at temperatures T_1 and T_2. The heats of sorption become smaller as the moisture content increases. Chung and Pfost found that the heats of desorption are higher than the heats of adsorption, from where they concluded that more sorptive sites are available during desorption, the main concept that explains their hysteresis theory.

The net heat of sorption is defined as:

$$q = \Delta H_{st} - \lambda \qquad (7)$$

where q is the net heat of adsorption or desorption, and λ is the heat of vaporization of water at a specified temperature. Net heats of adsorption and desorption are considered as additional heat required over the heat of condensation of water. As the moisture content increases, the net heats of sorption approach to zero.

Ross and Oliver (1964) define the differential heat of adsorption as

$$q_{st} - RT = q_{diff} \tag{8}$$

where q_{st} is the isosteric heat of adsorption and q_{diff} is the differential heat of adsorption. Brunauer (1943) states that the heat of adsorption as measured with a calorimeter lies between q_{st} and q_{diff}. The calorimetric heat of adsorption should therefore equal the isosteric heat of adsorption within an uncertainty RT calories per mole. However, RT usually does not amount to more than 5 to 10% of the total adsorption, which in many cases could be only slightly greater than the experimental measurements.

D. Diffusion and Drying

Diffusional processes are thought to play an important role in the moisture transfer to and from grains. The theory of diffusion is based on the hypothesis that the rate of transfer of the diffusing substance through a unit area of section is proportional to the concentration gradient normal to the section. The above can be represented as:

$$F = - D \frac{dC}{dx} \tag{9}$$

where F is the rate of transfer per unit area of section, C is the concentration, and x is the coordinate in the normal direction to the surface. The proportionality constant D is known as the diffusion coefficient.

Park, et al. (1972) assumed the sorption process of water vapor

on corn to be controlled by both diffusion and surface sorption mechanisms. They proposed the following equation to describe adsorption rates of water vapor in a porous sphere.

$$\frac{\partial M}{\partial t} = D \left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \frac{\partial M}{\partial r} \right) + k(M_e - M) \qquad (10)$$

where M is moisture content, r is the distance from the center of the sphere, t is time, D is the diffusion coefficient, K is the sorption rate constant, and M_e is equilibrium moisture content. The solution of equation (10) obtained by integrating over an entire sphere is

$$\frac{\overline{M} - M_o}{M_e - M_o} = 1 - \frac{6}{\pi^2} e^{-kt} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\overline{D}n^2 t} \qquad (11)$$

where M_o is the initial moisture content, $\overline{M}$ is the average moisture content at time t, and $\overline{D} = D\pi^2/R^2$. Equation (11) showed to describe very well the adsorption of water vapor by whole, heat-damaged, and broken corn.

Other workers have studied the movement of water in stored and tempering grain but a good portion of the work on the rate of moisture diffusion through grain has been concerned with drying applications; Henderson and Perry (1966) divide the drying process into two portions: 1) The constant drying rate period; and 2) the falling drying rate period.

In the constant rate period a material is assumed to contain so much water that it will dry in a manner comparable to an open-faced body of water. Drying in the falling rate period involves the movement of moisture within the material to the surface, and the removal of moisture from the surface. Practically all agricultural drying takes place in the falling rate period. The equation describing the falling rate period is often of the form:

$$\frac{\bar{M} - M_e}{M_o - M_e} = A \sum_{n=o}^{\infty} \frac{1}{(2n+1)^2} e^{-(2n+1)^2 kt} \qquad (12)$$

where A is a constant, K is another constant which includes the diffusion coefficient and a geometrical characteristic of the material, and t is time.

For thin-layer drying, equation (12) can be simplified to

$$\frac{\bar{M} - M_e}{M_o - M_e} = A e^{-Kt} \qquad (13)$$

and it is known to give satisfactory results for that particular mode of drying.

Hukill (1947 and 1950) devised a method to approximate the moisture content of grain at any given depth in a deep-bed drying system at any time after drying has started.

Other theoretical and empirical models are described very well by Brooker, Bakker-Arkema, and Hall (1974), who include not

only thin and deep bed drying, but also different models applicable to crossflow, concurrent-flow, and counterflow drying systems.

III. Adsorbents

Adsorbents or desiccants are substances capable of holding gases or water vapor when brought into contact with them. Both liquid and solid desiccants are used commercially but this section will only refer to solid adsorbents. Solid adsorbents can remove water vapor from air by the phenomena of physical adsorption or capillary condensation, without changing physically or chemically during the sorption process. The general requirements of solid adsorbents to be used in commercial dehumidifying systems and equipment are considered to be:

1) Suitable vapor pressure characteristics including high adsorptive capacity.

2) Stability. Should not break down structurally or chemically, and should resist contamination from impurities.

3) Relatively high rates of adsorption, and efficiency should be maintained over a wide range of temperature, humidity, and gas rate.

4) Desiccant should permit economical regeneration with the methods and temperatures available.

5) Should be noncorrosive, odorless, nontoxic, not readily flammable, should have a relatively high bulk density, and good mechanical strength.

6) Resistance to gas flow should be low.

7) Should be easily available at moderate cost.

Activated carbon, silica gel, and activated alumina are among the solid desiccants known and widely used for commercial purposes.

Miller (1920) found that vapors of liquids of high boiling points are more strongly adsorbed than vapors from liquids of low boiling points. Adsorption of water vapor by adsorbents normally decreases slightly at higher temperatures, and is greater at higher relative humidities.

The rate of adsorption by solid desiccants is dependent on the gas flow rate, since at higher rates a greater amount of adsorbable vapor is allowed to come into contact with the adsorbent. However, factors such as the physical structure of the adsorbent, its initial moisture content, the partial pressure of the gas, the equilibrium capacity, and the shape of the adsorbent mass also play an important role in determining the rate at which a particular gas is adsorbed by a desiccant.

Hougen and Marshall (1947) developed equations to predict rates of water adsorption by solid desiccants for the special case of isothermal adsorption where the gas film controls, and when the equilibrium moisture content is a linear function of the relative humidity. The equations are complicated since they involve the height of a mass transfer unit for the gas film, as well as modified Bessel functions of the first kind of zero order, and are not applicable to a large number of adsorbents.

McBain (1909) observed the adsorption of hydrogen on charcoal and predicted an equation based on Fick's diffusion law. If a considerable fraction of the gas is already dissolved in the solid, the equation can be simplified to:

$$v = A\left(\frac{\pi^2}{8} - e^{-k't}\right) \tag{14}$$

where v is the volume dissolved at a time t, and A and k' are constants. Equation (14) was not tested by McBain.

Bergter (1912) carried out experiments on the rate of nitrogen adsorption on charcoal at 18°C and at pressures between 0.36 and 6.75mm. He used the following empirical equation to express his results:

$$v = V_o\,(1 - 0.95\,e^{-3.5t} - 0.05e^{-0.15t}) \tag{15}$$

where v is the volume adsorbed at time t, and the constant V_o is determined by the pressure.

From the work of Langmuir (1918) on the rate of gas adsorption on a free surface at constant pressure, the volume v adsorbed at any time t can be expressed by

$$v = V_e\,(1 - e^{-kt}) \tag{16}$$

where V_e is the volume adsorbed at equilibrium, and k is a constant.

Damköhler (1935) derived an equation very similar to the original one proposed by McBain (1909) to predict the rates of vapor diffusion through the pores of an adsorbent at constant pressure. The equation is

$$V = 1 - \frac{8}{\pi^2} \sum_{m=0}^{\infty} \frac{e^{-d(2m+1)^2}}{(2m+1)^2} \tag{17}$$

where V is the fraction of the equilibrium amount adsorbed at time t, and d is a constant which includes the length of the capillaries and the diffusion coefficient.

The above equations have been applied to predict rates of vapor adsorption during the first few minutes. However, if the adsorbent has long and narrow pores, and if impurities are present in the adsorbent or the gas, the rates of adsorption are cut down considerably, and it may take many hours, even weeks, to attain equilibrium.

Empirical equations have been applied to predict rates of vapor adsorption by desiccants over longer periods of time, but all the physical processes taking place during adsorption over long periods of time have not been fully investigated so far.

IV. Utilization of Corncobs

It is difficult to estimate how many tons of corncobs are produced worldwide, and what percentage is actually being

utilized for agricultural, industrial, or commercial purposes. Arnold (1975) states that only about 3% of the 1968 corncob production in the United States was utilized for industrial or commercial purposes. He also outlined several ways to utilize corncobs, some of which are summarized below.

Corncobs are known to contain pentosans from which the corresponding pentoses can be formed when heated with a dilute mineral acid. Further heating results in the production of 2-furaldehyde or furfural. Furfural is a selective solvent used to dissolve gums and unsaturated portions of vegetable oils. Furfural is also the starting point for the manufacture of hexamethylene, diamine, and adipic acid, which are intermediates for nylon production. Small amounts of furfural are used as fungicides, disinfectants, and herbicides. A furfural plant at Omaha, Nebraska uses corncobs, and another at Memphis, Tennessee uses some corncobs.

Experiments at Iowa State University showed that plastic products can be made from corncobs by adding a chemical substance to produce a thermosetting product. The best samples compared favorably with phenol-furfural products but the process was never commercialized. Corncob flour was used in phenolic plastics but produced a product with higher moisture adsorption than that made using wood flour.

A hard fire-resistant board named "Corncrete" has been patented. Good boards were made with 65% cobs, 18.5% ammonium lignosulfonate, and 16.5% furfuryl-alcohol mixed together and

formed into panels and dried at 100°C and 15 psi. for 10 min. The panels had a flexural strength of 1500 psi.

Producer gas from wood and charcoal has been used in many countries as a fuel. Work at the Northern Regional Research Laboratory of the U.S.D.A. showed that the quality of gas produced from corncobs equals that from wood. However, no practical equipment has been developed to commercialize gas production from corncobs.

Corncob grit blasting may be used to clean large electric motors and generators rapidly and economically. Ground corncobs have also been used in the barrel method of deburring, polishing, and burnishing metal stampings, molded plastics, and metal die casts. Cob grits are also used for absorbing oils, greases, and dirt from metal stampings and heat-treated metal pieces.

Other uses for corncobs include the production of oxalic acid, adhesive extenders, abrasives for soap, dynamite, lightweight brick ceramics, floor sweeping compounds, and rug cleaners.

Relatively large quantities of corncobs are used for the manufacture of feeds, and some are ground and fed directly to cattle.

The literature showed no instances where corncobs had been used as water vapor adsorbents, and a computer literature search yielded no information on the hygroscopic properties of corncobs.

OBJECTIVES

The overall objectives for this study were to obtain hygroscopic properties for corncobs and investigate their application as a desiccant to dehumidify air in tropical climates for grain drying and conditioning.

The study was subdivided into two parts.

Objectives for Part I of the Study

1) To determine isotherms for corncobs at 70°F, 80°F, and 90°F.

2) To investigate the rate of water vapor adsorption by ground, whole, and chopped corncobs at 70°F, 80°F, and 90°F, at relative humidity levels of 85% and 60% for each of the above temperatures.

3) To investigate the effect of three drying temperatures (90°F, 140°F, and 180°F) on the equilibrium moisture content of corncobs after allowing them to readsorb moisture.

4) To determine the performance of corncobs after successive desorption-adsorption cycles.

Objectives for Part II of the Study

1) To design a system to test the application of corncobs as a desiccant for grain drying and conditioning.

2) To perform drying and conditioning tests with shelled corn at initial moisture contents ranging from 25% to 15% wet basis, utilizing a simulated natural air system and a forced-air system capable of moving up to 3 cfm per bushel of corn.

3) To evaluate the performance of the systems.

MATERIALS, PROCEDURES, AND EQUIPMENT

Part I

Whole corncobs from yellow dent corn were obtained from the field two days after harvest in October of 1976 at an approximate moisture content of 12% dry basis. After placing the cobs in plastic bags they were stored in a laboratory kept at about 75°F and 30% relative humidity where the initial moisture content of the cobs decreased to approximately 6% dry basis.

A portion of the cobs was ground with a portable hammermill (Munson Mill Machinery Co. Type 1) provided with a ½ inch screen. The ground cobs were sifted with a Gamet sifter (Burrows Equipment Co.) utilizing a 12/64" screen. Ground cobs used had a size between 12/64" and ½". Prior to each test some cobs were chopped utilizing a rotary electric saw. Chopped cobs had lengths that ranged from 1 inch to about 2½ inches.

All tests for part I of this study were carried out in an Aminco environmental control chamber equipped with an Aminco-Aire (American Instrument Company) air controller. The chamber was provided with a Taylor hygrometer (cat. # 5S42-CN) and a Taylor Recorder (serial A76JR216). The relative humidity inside the chamber was monitored with the Taylor recorder, a calibrated hygrothermograph (H. J. Green Instruments. Serial # 71176), and a laboratory-made aspirating psychrometer with two well matched thermometers with .1°C subdivisions. The temperature

inside the chamber was maintained constant at the desired level and monitored with the hygrothermograph, Taylor Recorder, and a thermometer. Both temperature and relative humidity were checked twice daily.

In order to simulate several levels of relative humidity for isotherm determinations, sulfuric acid solutions were prepared with distilled water and placed in desiccators with well sealed glass lids. The solutions were prepared on a weight basis using a Metler balance model P5 capable of weighing down to 0.1 gm. After the solutions were mixed their density was carefully checked utilizing a calibrated 50 ml. pycnometer bottle and a Torbal balance model ET-1 serial 115112 capable of weighing down to 0.001 gm. Tables in the Chemical Engineer's Handbook Third Edition were used to obtain the actual vapor pressure of the solutions. Table 1 shows the theoretical and actual percent of sulfuric acid, vapor pressure, and theoretical and actual relative humidity for the solutions at 72°F. The relative humidity inside the desiccators was double-checked prior to and after each experiment with a Bendix battery operated psychrometer model 566. Table 2 shows two replications of the above checks for the solutions at 72°F and 80°F. The temperature inside the desiccators was the same as that of the environmental chamber where they were placed.

Experiments for isotherms were carried out at 72°F, 80°F, and 90°F. Prior to each test the cobs were dried in Blue M laboratory ovens model OV-490A-2 to a moisture content of

Table 1. Data for sulfuric acid solutions at 72°F (22°C).

PERCENT SULFURIC ACID		VAPOR PRESSURE	RELATIVE HUMIDITY	
Theoretical	Actual	mm. Hg	Theoretical	Actual
15	14.39	18.32	92.4%	92%
25	23.87	16.61	83.8%	83%
35	33.45	13.90	70.1%	70%
40	38.29	12.06	60.8%	61%
50	47.88	8.00	40.3%	41%
60	56.75	4.49	22.6%	23%
65	63.31	2.35	11.9%	12%
70	68.20	1.22	6.2%	7%

approximately 2% dry basis. After the chamber and desiccators had stabilized at the desired conditions, samples of whole, ground, and chopped cobs were weighed on the Torbal balance to the nearest one hundredth of a gram and placed on a screen above the sulfuric acid solutions inside the desiccators. The cobs were left undistrubed for a minimum of 2 weeks inside the desiccators and then weighed to determine their moisture content. Previous experiments had revealed that at the end of one week the majority of the cobs reached their equilibrium moisture content. No appreciable mold growth resulted on the cobs at

Table 2. Relative humidities in desiccators as checked by psychrometer.

BOX	72°F rep. 1	72°F rep. 2	80°F rep. 1	80°F rep.2
1	92	92	92	92
2	83	83	84	83
3	70	70	72	71
4	61	61	64	63
5	41	41	44	45
6	23	24	27	28
7	12	16	16	17
8	7	10	11	11

high humidities except on those at 92%, but it was not considered enough to introduce a large error in the final weight of the samples. Two replications were run for each temperature setting.

To determine the dry weight of the corncobs and consequently their moisture content, samples were placed in the laboratory ovens for 24 hours at 212°F (100°C). Tests conducted prior to the experiments showed that after about 18 to 20 hours at 212°F the corncobs had lost all their free and adsorbed water. On one occasion some samples were left in the oven for 36 hours at 212°F without showing any decrease in the

weight recorded 12 hours before.

Rates of water vapor adsorption were obtained for ground, whole and chopped corncobs which generally had not been predried in the oven. Samples consisted of 3 whole cobs, ground cobs weighing approximately 50 gm, and chopped cobs weighing from about 120 to 200 gm. Three replications of each sample were used in all tests for rates of water vapor adsorption. Ground and whole-cob samples were weighed on the Torbal balance to the nearest one hundredth of a gram and the larger chopped-cob samples were weighed on the Metler balance to the nearest 0.1 gm. Whole cobs were placed directly on the racks inside the environmental chamber, ground cobs were placed on plastic trays, and chopped cobs were placed in wire baskets.

Since the balances used had to remain outside the environmental chamber, all whole and chopped samples were placed in plastic bags sealed with rubber bands, and all ground-cob samples were transferred to seamless aluminum cans before weighing.

After the initial weight of the samples was recorded they were placed inside the environmental chamber at the desired conditions. The weight of the samples was recorded six hours later, when possible, and once a day from then on at approximately 24-hour intervals. After the weight of the samples showed no further increase they were placed in the ovens at 212 F (100°C) for 24 hours for dry weight and moisture content determinations. Table 3 shows the environmental conditions at which data for rates of water vapor adsorption were collected.

Table 3. Environmental conditions used to determine the rates of water vapor adsorption by whole, ground, and chopped corncobs.

Temperature	Relative Humidity	Remarks
72°F	86%	Two Replications, Cobs predried in oven
	61%	Two Replications
80°F	85%	Two Replications
	61%	Two Replications
90°F	83%	Second test at 84% relative humidity
	60%	Two replications

Drying temperatures of 90 , 140 , and 180°F were selected to study their effect on the equilibrium moisture content of corncobs. Samples of ground, whole, and chopped cobs were dried at the desired temperatures and placed in the environmental chamber at 72°F and 86% relative humidity until their weight no longer increased. After determining their dry weight, their equilibrium moisture content was calculated.

In order to determine the cyclic performance of corncobs, samples of ground and whole cobs were placed in the environmental

chamber at 81°F and 79% relative humidity and allowed to reach their equilibrium moisture content. The samples were dried finally at 100°C for 24 hours to determine their dry weight and moisture content. Three consecutive wetting and drying cycles were performed for the same cobs.

Part II

The experimental set-up for Part II of this study consisted of two small corrugated sheet metal bins with a net volume of about 12 ft^3 each, connected to 2 ft^3- corncob chambers. Air drawn from a 320 ft^3 Hussman Refrigerator Co. environmental chamber (serial 68751210) passed through a 3 in. diameter pipe, then through the corncob mass, the perforated floor in the bins (about 35% open area), and up through shelled corn to be conditioned. The air conditions inside the environmental chamber were maintained at $83 \pm 2\%$ relative humidity and 80°F.

A Honeywell humidistat sensed the relative humidity inside the chamber, and a Honeywell controller operated a solenoid valve that injected steam into the chamber when needed. A resistance type heater inside the recirculating air duct and operated by a Honeywell controller was used to control the recirculating air temperature. An air conditioner was also used to counteract the heat build up caused by the injection of steam. The temperature and humidity inside the environmental chamber were monitored with a calibrated Weather Measure

hygrothermograph model H-302 (serial 55439), and checked periodically with the Bendix battery operated psychrometer, a mercury-in-glass thermometer, and a Beckman Humi-Check II precision hygrometer.

The corncob chambers were made out of galvanized sheet metal with one inch of styrofoam insulation on all sides. The plastic pipe connecting the environmental chamber to the corncob chambers was covered with 3/4" of wrap-around fiberglass insulation with a plastic vapor barrier.

Dayton blowers model 1C180 rated at 60 cfm free air were used to move the air from the environmental chamber through the system for the forced ventilation experiments of this study. The fans were provided with intake dampers to control the airflow. The air velocities before and after the corncob chambers were checked with a Hastings hot-wire anemometer model B22 serial 75. The small holes drilled to accomodate the anemometer probe were plugged with cork stoppers.

For the natural ventilation experiments one of the bin roofs was provided with a rotary roof ventilator four inches in neck diameter, (Empire type), which created a vacuum within the turbine. The vacuum was replaced by an upward draft of air coming from the environmental chamber and passing through the system. An Emerson Electric room fan type 79648-AX was used to simulate natural wind at speeds from 5 to 8 mph. The wind speeds were checked with the Hastings hot-wire anemometer and an Alnor velometer type 3002 serial 15433.

The temperature and relative humidity of the air were

checked before and after the corncob chambers with well-matched dry-bulb and wet-bulb thermometers for the first two experiments of Part II. For the remaining experiments the dry-bulb and wet-bulb temperatures were sensed with copper-constantan thermocouples and recorded every hour with a Digitec 1268 data logger serial 714, provided with a Hy-Cal thermocouple reference junction model 305. Figure 3 shows two general views of the experimental set up for Part II of the study.

Corn harvested in the Manhattan, Kansas area and in Nebraska at moisture contents ranging from 16% to 25% wet basis was cleaned with a Clipper M-2B (A. T. Farrell and Co.) grain cleaner before it was placed in the bins. A total of 450 pounds or about 8 bushels of corn were placed in each bin, except for the natural ventilation tests in experiments #1 and #2, where 340 lbs. of corn or about 6 bushels were used. Table 4 summarizes the experiments carried out for Part II of the study, as well as the history of the corn used in each case.

The corn inside the bin was sampled every day at four different horizontal levels and two vertical zones for moisture content determinations. After an experiment ran for 2 weeks sampling was done every other day. A burrows grain trier model 1-0528 with partitions was used for sampling. Figure 4 shows the sampling levels and zones.

The following are the codes used for sample labeling:

T: Top part of bin.

U: Upper part of bin.

L: Lower part of bin.

B: Bottom part of bin.

C: Center zone of bin.

O: Outer zone of bin.

The outer zone was not limited to one side, but sampling was done around the outer circumference. Samples were taken initially and every week for mold determinations, but those from the center and outer zones were mixed together to have only 4 samples for each bin when making the analysis for mold invasion. The general procedure followed for determining mold contamination is outlined below:

1) The surface of the kernels was disinfected with a 5% NaOCl (Clorox) solution for 1 minute. Kernels were then rinsed twice with sterile distilled water.

2) For each sampling level 50 kernels were plated on malt agar containing 4% sodium chloride and 200 ppm. Tergitol NPX.

3) Plates were incubated for 5 to 7 days at 25°C.

The grain temperatures at the upper and bottom levels were measured with copper-constantan thermocouples and recorded every hour.

All samples taken for Part II of the study were weighed with a Metler P1200N scale capable of measuring to the nearest 0.01 gm. Corn samples were placed in a Blue M oven model OV-500 C-2 for 72 hours at 103°C for dry weight determinations.

Approximately 16 pounds of whole corncobs were used in each corncob chamber for the drying-conditioning experiments.

Part of the corncobs used were from the same batch as those used for the hygroscopic properties experiments, and the remaining were obtained from the field in September and October of 1977.

Corncobs were initially dried to a moisture content of 1.5 to 5% dry basis using an Aeroglide Tray drier model S1-30-10RSX, serial 25498-1 for 6 to 8 hours at 140°F. The corncobs were replaced when the relative humidity in the outlet side of the corncob chambers reached about 72 to 78%. Samples of corncobs were taken at the beginning and end of each cycle for moisture content determinations. The dry weight of the corncobs was obtained after placing the samples in the laboratory oven for 24 hours at 103°C.

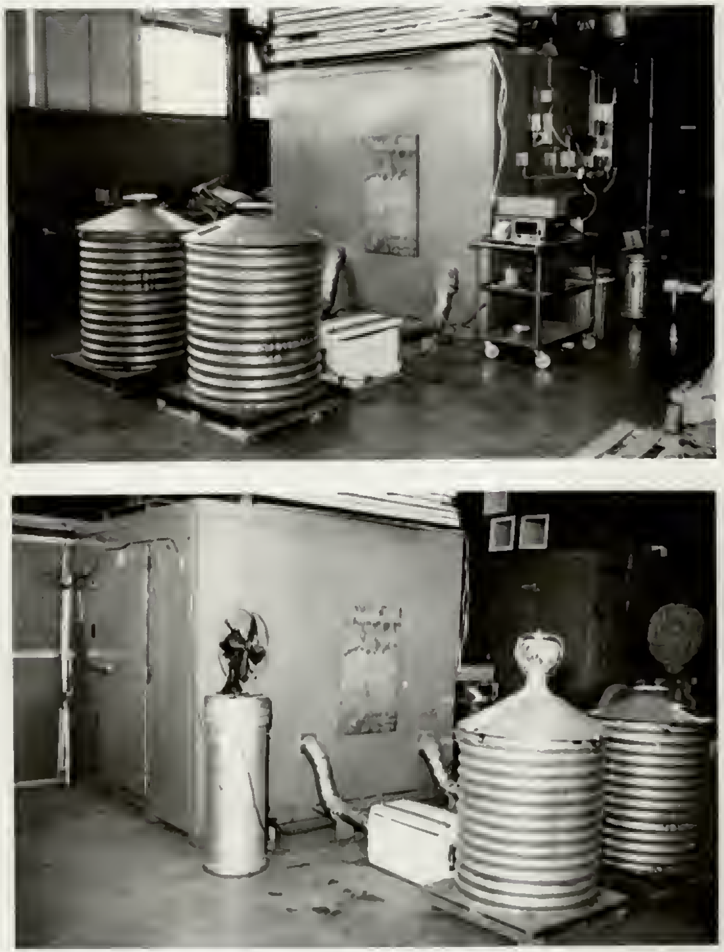


Figure 3. Experimental setup for Part II of the study.

TOP: Two forced-air tests.

BOTTOM: A natural ventilation test and a forced-air test.

Table 4. Experiment Description and History of Corn for Part II of Study.

Experiment No.	Initial Corn Moisture Content % Wet Basis	Natural Ventilation (Wind Speed mph)	Forced Ventilation (Airflow cfm/bu.)	History of Corn
1	25%	Yes (5.5 mph)	Yes (3 cfm/bu)	Corn harvested and cleaned. Stood sacked overnight before placing in bins.
2	16%	Yes (7.5 mph)	Yes (3 cfm/bu)	Corn harvested, cleaned, and placed in bin on the same day.
3	23%	No	Yes (3 cfm/bu) and (2 cfm/bu)	Corn harvested in Nebraska and transported to Manhattan by truck. Stood on truck overnight at about 56°F before cleaning and placing in bin.
4	22%	Yes (5.0 mph)	No (Corn in bin without ventilation)	Same as #3 but corn was stored at 40°F after cleaning for 2 weeks.
5	18%	No	Yes (2 cfm/bu) and (1 cfm/bu)	Same as #4, but from a different truckload.

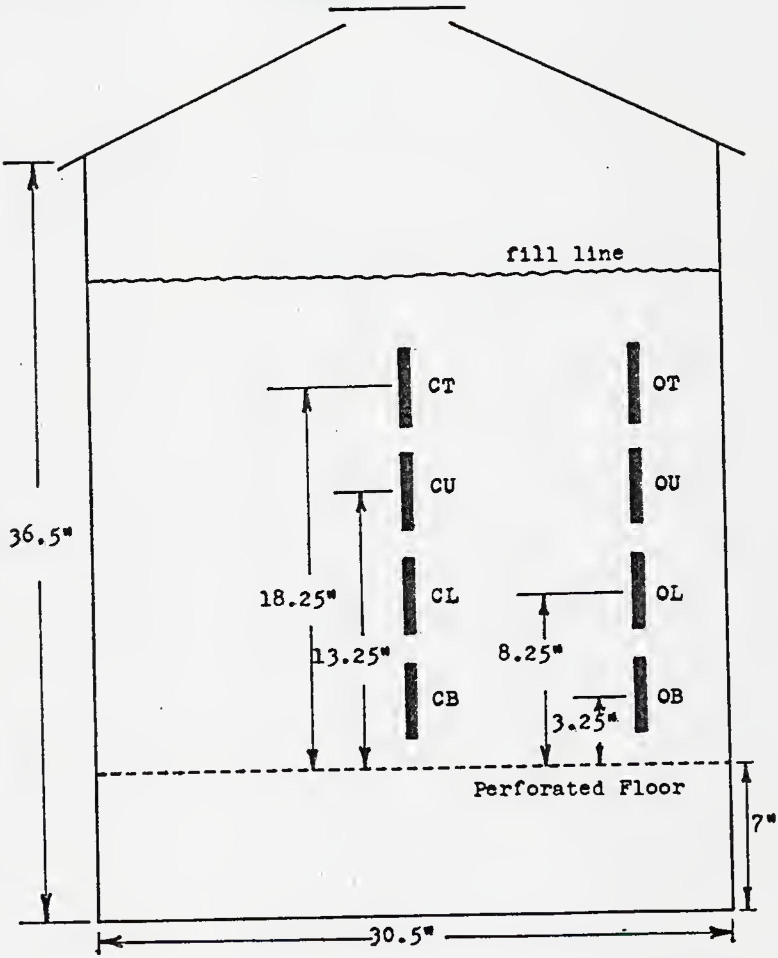


Figure 4. Coded sampling levels and zones for moisture content and mold determinations in Part II of study.

RESULTS AND DISCUSSION

Part I

A. Isotherms

The experimental equilibrium moisture contents for corncobs at 72°F, 80°F, and 90°F are given in Table 5, and the isotherms are plotted in Figures 5 through 7. It was not possible to exactly replicate each test since the relative humidity inside the desiccators varied as time progressed. The values for replication number 1 at 80°F are omitted from Table 5 since they are considered unreliable. Only one replication was run for chopped corncobs at 90°F.

Figures 5 through 7 show that the isotherms belong to type II under Brunauer's classification, or to the so-called S-shaped isotherms as most cereal grains. Table 5 and Figures 5 through 7 show that there is not much difference between the equilibrium moisture content of whole, ground, and chopped cobs at a given relative humidity (within $\pm$ 0.4% moisture content of each other in most cases). It can also be seen from Table 5 that there is no consistency as to which has the highest or lowest moisture content at a given relative humidity. For the above two reasons all data for whole, ground, and chopped cobs at a given temperature were treated together in the analysis.

The data show that the equilibrium moisture content increases slightly with a decrease in temperature. Many investigators agree that the adsorption and desorption processes of

Table 5. Equilibrium moisture content of whole, ground, and chopped corncobs at various relative humidities after adsorption tests.

Temperature	Relative Humidity (%)	Equilibrium Moisture Content (% d.b.)					
		Whole Cobs		Ground Cobs		Chopped Cobs	
		Rep.1	Rep.2	Rep.1	Rep.2	Rep.1	Rep.2
	7	2.62		2.62		2.62	
	10		3.20		3.10		3.30
	12			3.30		3.52	
	16		4.20		4.20		4.20
	23	4.93		4.92		4.93	
72°F (22.2°C)	24		6.0		5.6		5.50
	41	7.50	7.70	7.50	8.0	7.27	7.70
	61	10.9	10.6	10.6	10.9	10.6	10.6
	70	12.4	12.7	12.7	12.9	12.6	12.6
	83	18.6	17.6	18.1	18.1	17.7	17.7
	92	27.9	25.6	25.8	25.9	26.0	26.6

Table 5 (cont.)

Temperature	Relative Humidity (%)	Equilibrium Moisture Content (% d.b.)					
		Whole Cobs		Ground Cobs		Chopped Cobs	
		Rep.1	Rep.2	Rep.1	Rep.2	Rep.1	Rep.2
80°F (26.7°C)	11	3.15	3.19	3.08	3.23		3.18
	16	4.10		4.01			
	17		4.29		4.20		4.07
	27	5.88		5.36			
	27.5		5.81		5.71		5.73
	44	7.89		7.68			
	45		8.27		8.23		7.84
	63		11.03		10.70		10.50
	64	10.7		10.50			
	71		12.47		12.13		
	72	12.50		12.50			
	83		18.29		17.91		17.24
	84	18.6		17.6			
	92	24.71	25.6	25.04	25.6		25.70

Table 5 (cont.)

Temperature	Relative Humidity (%)	Equilibrium Moisture Content (% d.b.)					
		Whole Cobs		Ground Cobs		Chopped Cobs	
		Rep. 1	Rep.2	Rep.1	Rep.2	Rep.1	Rep.2
	12	2.91		2.90		3.08	
	13		3.10		3.28		
	18	3.87	4.05	3.77	4.05	3.90	
	28	5.78		5.45		5.57	
	29.5		5.82		5.73		
	45.5	8.05		7.82		7.91	
	48.5		8.43		8.23		
90°F (32.2°C)	63	10.02		10.11		9.98	
	65		10.45		10.30		
	71			12.29		12.29	
	71.5		12.19		12.15		
	83	17.39		17.09		16.59	
	84		17.93		17.63		
	92	24.73		24.14	24.84	4.43	

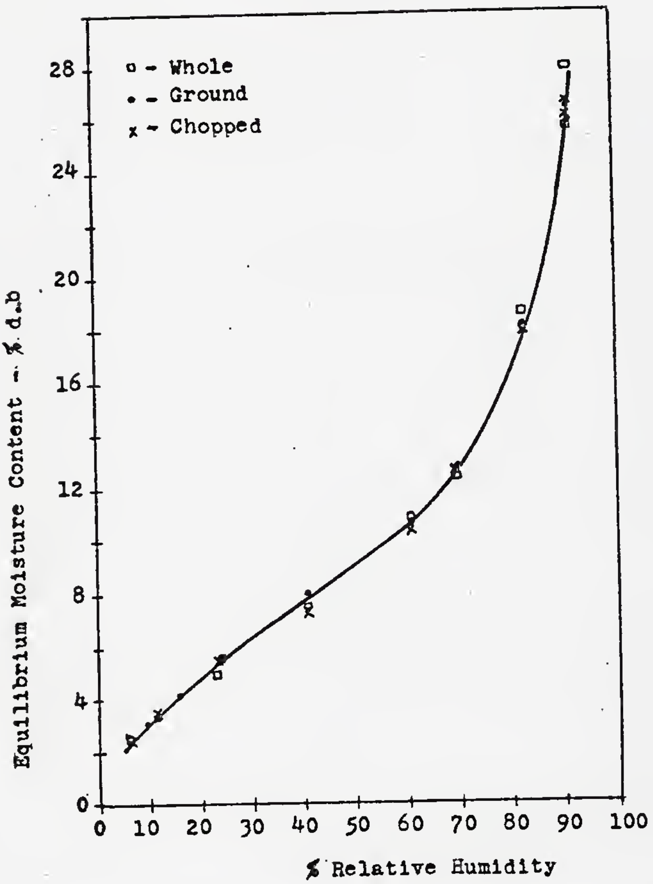


Figure 5. Adsorption Isotherm for Whole, Ground, and Chopped Corncobs at 72°F (22 °C).

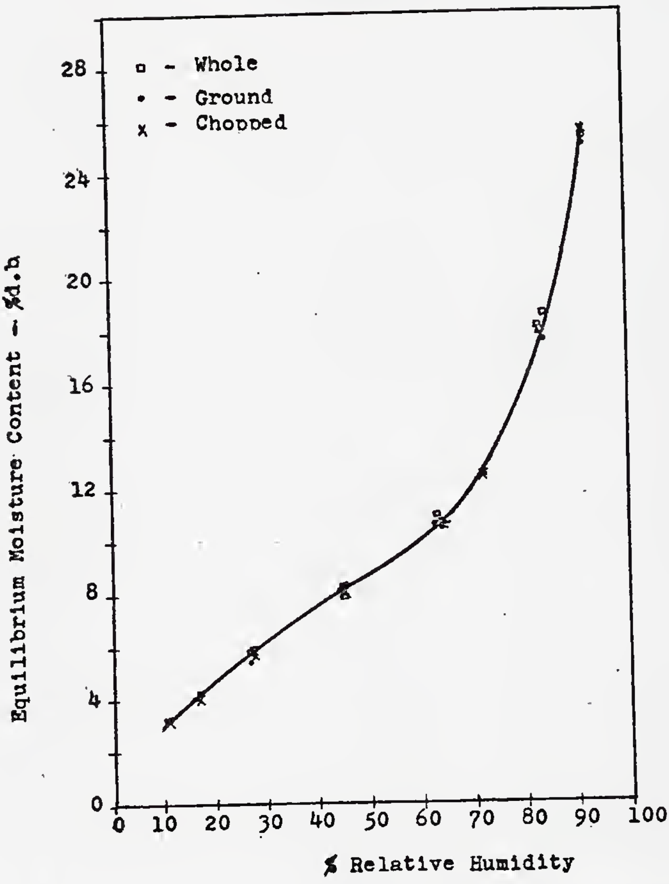


Figure 6. Adsorption Isotherm for Whole, Ground, and Chopped Corncobs at 80°F (26.7°C).

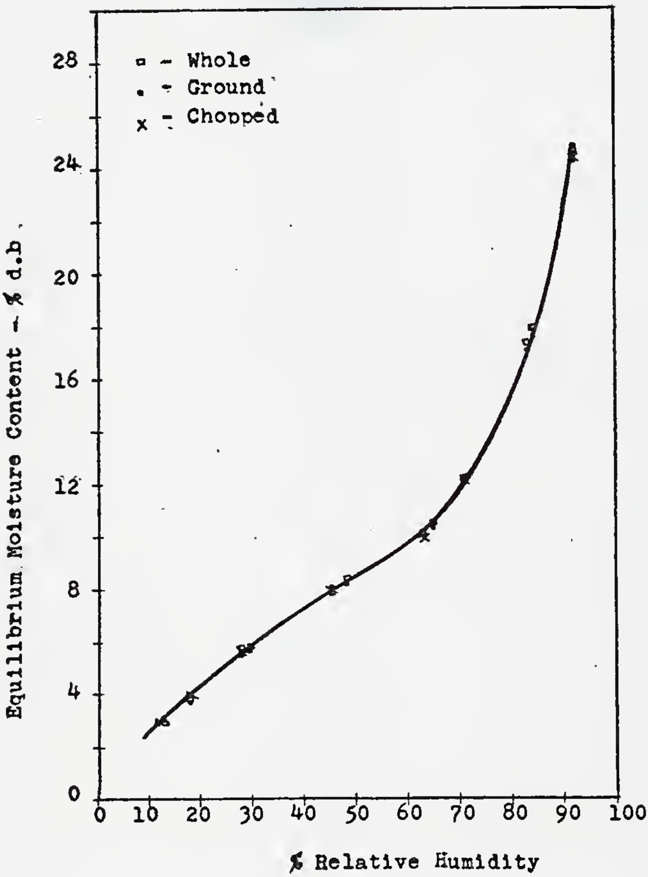


Figure 7. Adsorption Isotherm for Whole, Ground, and chopped corncobs at 90°F (32.2°C).

cereal grains and their products are controlled by van der Waal's forces. The vapor pressure at the surface of the corncobs is greater than that of the surroundings, but water molecules do not leave the corncobs because they are held by van der Waal's forces. It can be seen from the free energy equation (4) that for a constant relative humidity the change in free energy ΔF will increase with an increase in temperature. If van der Waal's forces are not as dependent on temperature as the free energy, any temperature increase will cause the water molecules to leave the corncobs, thus reducing their moisture content at the same relative humidity. At colder temperatures the free energy will not be high enough to drive the water molecules out of the corncobs, causing an increase in their moisture content.

An attempt was made to describe the equilibrium isotherms by Henderson's equation (2). The linearlized form of equation (2) is:

$$\ln\left(-\ln(\ln RH)\right) = \ln(cT) + n \ln M_e \tag{18}$$

When plotting the left-hand side of equation (18) against $\ln M_e$ for any of the isotherm data a straight line doesn't result, indicating the inadequacy of equation (2) to describe the experimental isotherms.

Chung's and Pfost's equation (3) is easily rearranged to yield equation (19):

$$-RT \ln RH = A \exp(-BM_e) \tag{19}$$

The linearlized form of equation (19) is:

$$\ln (-RT \ln RH) = \ln A -BM_e \tag{20}$$

Plots of the left-hand side of equation (20) versus ln M_e indicate that the Chung and Pfost equation can describe the experimental isotherm data in two ranges, as illustrated in Figure 8 for the data at 72°F. Data for 80°F and 90°F show the same effect. In all cases the break points occur very near 12% moisture content, which is in equilibrium with air at about 70% relative humidity. No other relation could be found that would describe the equilibrium moisture content of corncobs better in one or two ranges of relative humidity.

The break point and rapid increase in equilibrium moisture content in the high humidity range is probably caused by capillary condensation and seems to occur after the first two layers of water molecules have been formed.

In order to find the constant A and B in the isotherm equation (19) the data for the three different temperatures were used in a SAS-76 computer program which performs a least squares estimation. Data around the break point were included both as the end point of the first range and the starting point of the second range. After the constants A and B were obtained for both ranges the 'best' break point was estimated by substitution of the experimental data into the isotherm equation. Table 6

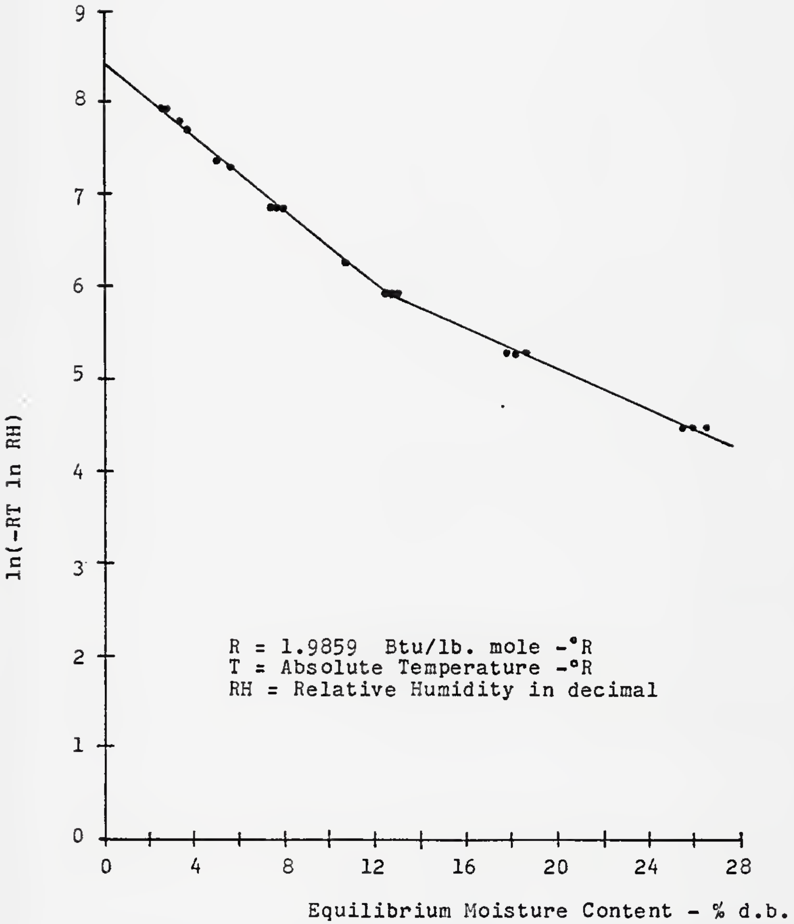


Figure 8. Plot of the left-hand side of the Chung and Pfost equation vs. M_e for corncobs isotherm at 72°F (22.2°C).

Table 6. Constants for isotherm equation at different temperatures, their applicability, and degree of accuracy. *

Temperature	Constant A	Constant B	Range (R.H.%; M.C.% d.b.)		R^2	$\hat{\sigma}_{model}$	$\hat{\sigma}_A$	$\hat{\sigma}_B$
72°F	4451	0.1985	< 71%;	< 12.2%	.994	0.0547	0.0210	0.00261
(22.2°C)	1365	0.1048	≥ 71%;	≥ 12.2%	.988	0.0695	0.0574	0.00290
80°F	4495	0.2056	≤ 71%;	≤ 12.2%	.997	0.0361	0.0161	0.00204
(26.7°C)	1351	0.1072	> 71%;	> 12.2%	.995	0.0443	0.0452	0.00230
90°F	4229	0.2037	< 70%;	< 12.0%	.995	0.0485	0.0216	0.00280
(32.2°C)	1490	0.1154	≥ 70%;	≥ 12.0%	.991	0.0563	0.0586	0.00309

* Isotherm equation: $-RT \ln RH = A \exp(-BM_e)$

$R^2 \times 100$ = % of variation about the mean explained by model.

$\hat{\sigma}_{model}$: Standard deviation for linear model.

$\hat{\sigma}_A$: Standard deviation for constant A in the linear model.

$\hat{\sigma}_B$: Standard deviation for constant B in the linear model.

shows the constants for both ranges at each temperature, their applicability, and standard deviations.

Figure 9 shows experimental data and predicted isotherms from equation (19) with the constants given in Table 6 for 72°F, 80°F, and 90°F. The predicted isotherms are in very good agreement with the experimental data, verifying that the Chung and Pfost equation predicts the isotherms for corncobs in two ranges.

It was not possible to obtain a relation to predict the values of the constants A and B for a large range of temperatures since three data points are not sufficient, and furthermore, the numerical values found for A and B do not differ enough as to give the general shape of a relation. It is conceivable that Polanyi's work on the potential theory of adsorption and characteristic curves for isotherms could be applied to predict isotherms at other temperatures. Since the isotherms for 72°F and 90°F seem to be only slightly different, combined constants A and B were obtained by using all the data for the three temperatures in the statistical analysis program. Results are summarized in Table 7.

It should be emphasized that the isotherms obtained for this experiment correspond to the first full cycle of adsorption. It is conceivable that isotherms for other than the first full cycle would lie anywhere within the hysteresis loop.

Figure 10 shows the equilibrium moisture content for corncobs compared to those of yellow dent corn and some commercial desiccants. Corncobs show a higher equilibrium moisture content than Drierite at relative humidities greater than 30%, and their

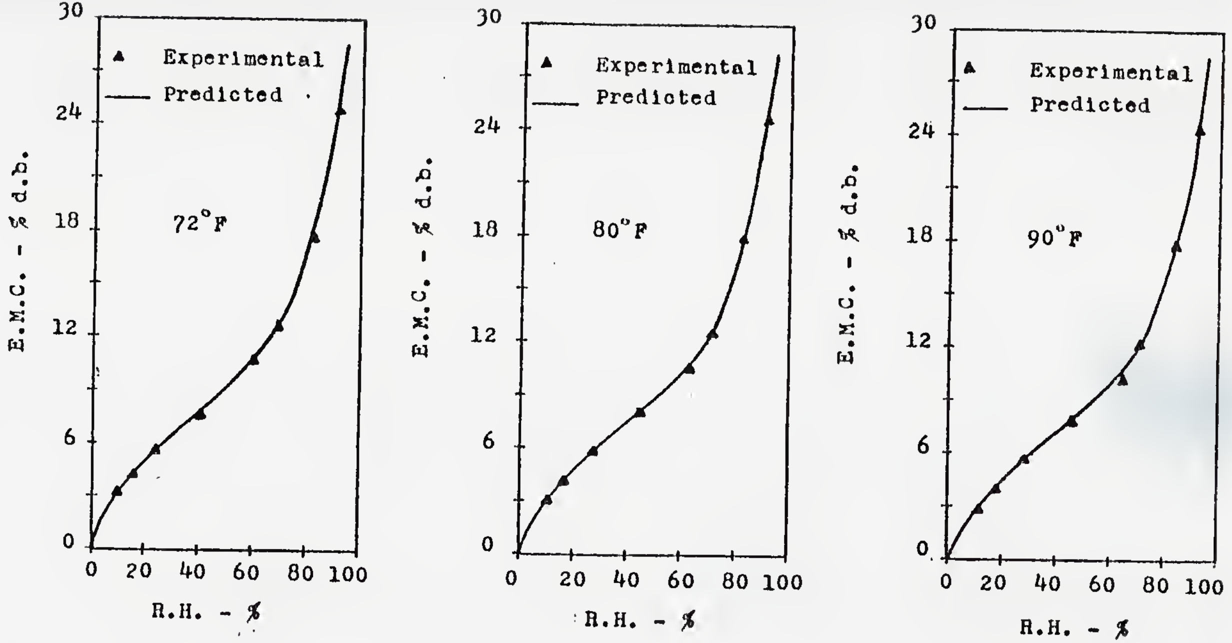


Figure 9. Experimental data and predicted adsorption isotherms for corncobs at 72°F, 80°F, and 90°F.

Table 7. Constants in the isotherm equation, applicability, and degree of accuracy for combined isotherm data at 72°F, 80°F, and 90°F.*

	For RH≤71% and MC≤12.2% d.b.	For RH>71% and MC>12.2% d.b.
A	4377	1376
B	0.2018	0.1078
R^2 of linear model	0.992	0.983
Standard deviation of linear model	0.0605	0.0770
Standard deviation of constant A	0.0147	0.0420
Standard deviation of constant B	0.00186	0.00210

* Equation: $-RT \ln RH = A \exp(-BM_e)$.

equilibrium moisture content is not much lower than that of activated alumina at relative humidities below 80% where the curves cross. Silica gel has by far a greater capability for moisture adsorption. Comparison of the equilibrium moisture curves for corn and corncobs would indicate that corncobs would probably not be applicable as a desiccant inside a grain mass as in the experiments carried out by Fleske (1973) and Hsiao (1974) with silica gel.

However, the performance of a desiccant cannot only be measured in terms of its isotherm, but the rates at which it can adsorb moisture are important when considering possible

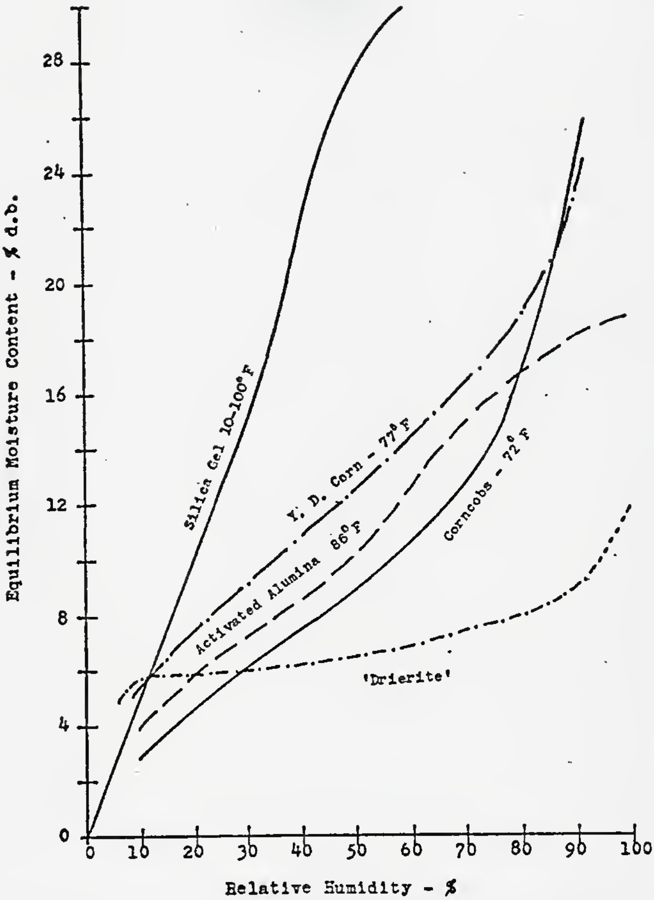


Figure 10. Equilibrium Moisture for some solid desiccants*, yellow dent corn†, and corncobs.

*From The Chemical Engineering Handbook - Perry, 3rd Ed.
†From Thompson and Shedd (1954) converted to dry basis.

applications.

B. Heat of Adsorption

The predicted isotherms at 72°F and 90°F were used to find the heat of adsorption of corncobs at various moisture contents by means of equation (6). These values are shown in Table 8, and are very much in agreement with those found for corn at 31°C by Chung and Pfost (1967).

Table 8. Heat of adsorption of corncobs at various moisture contents calculated from isotherms at 72°F and 90°F. *

Moisture Content % d.b.	Heat of Adsorption Btu/lb H_2O	Joules/KgH_2O	Kcal/gm.mole
5	1344	3.123×10^6	13.4
10	1184	2.750×10^6	11.8
15	1099	2.554×10^6	11.0
20	1093	2.537×10^6	10.9
25	1084	2.516×10^6	10.8

* Effective temperature of 81°F (27.2°C).

The heats of desorption reported by Chung and Pfost are consistently higher than those for adsorption. Assuming that the heat of desorption for corncobs is also comparable to that for corn, it can be concluded that the energy required to remove

water from corncobs is approximately the same as that from corn on a per weight-of-water basis.

The isosteric heat of adsorption ΔH_{st} is composed by the heat of condensation λ , the change in free energy ΔF, and the change in unavailable energy $T\Delta S$, where T is the absolute temperature and ΔS is the change in entropy. The term $T\Delta S$ represents the energy which cannot be converted to external work at constant temperature, but which appears only as heat when released.

The net heat of adsorption, as defined earlier in equation (7), is considered as additional heat over the heat of condensation of water. Thus, it is equal to $\Delta F + T\Delta S$.

The term ΔF can be obtained from equation (4), or from either the left or right hand sides of the isotherm equation (19).

Table 9 shows the values of the net heat of adsorption, the change in free energy, and the change in unavailable energy calculated for corncobs at 81°F and five different moisture contents. The change in free energy is calculated from the right hand side of equation (19) with values of A and B for the combined isotherm equation as given in Table 7. Since the value of R in the isotherm equation has units of Btu/lb mole.°R, constant A is divided by a factor of 18 in order to obtain the change in free energy in Btu/lb. H_2O.

Values in Table 9 are illustrated in Figure 11. It is observed that the heat of desorption decreases rapidly at low moisture contents. The heat of adsorption calculated for 2%

moisture content is 1512 Btu/lb H_2O, 12.5% higher than that at 5% moisture content. Only above 15% moisture content the heat of adsorption decreases moderately.

Table 9. Net heat of adsorption, change in free energy, and change in unavailable energy for corncobs at 81°F and various moisture contents.

Moisture Content % d.b.	Net heat of Adsorption* (Btu/lb H_2O)	Change in Free Energy $-\Delta F$ (Btu/lb H_2O)	Change in Unavailable Energy - $T\Delta S$ (Btu/lb H_2O)
5	296.5	88.7	207.8
10	136.5	32.3	104.2
15	51.5	15.2	36.3
20	45.5	8.9	36.6
25	36.5	5.2	31.3

* Heat of condensation of water at 81°F = 1047.5 Btu/lb.

C. Adsorption Rates

Tests to determine the rates of water vapor adsorption by corncobs were conducted inside an environmental chamber with almost negligible air velocity past the samples. Therefore, the results and conclusions from this section correspond to the static adsorption case, as opposed to dynamic adsorption where the airflow past the samples has to be considered. Static adsorption rates can be of significant importance when taking into

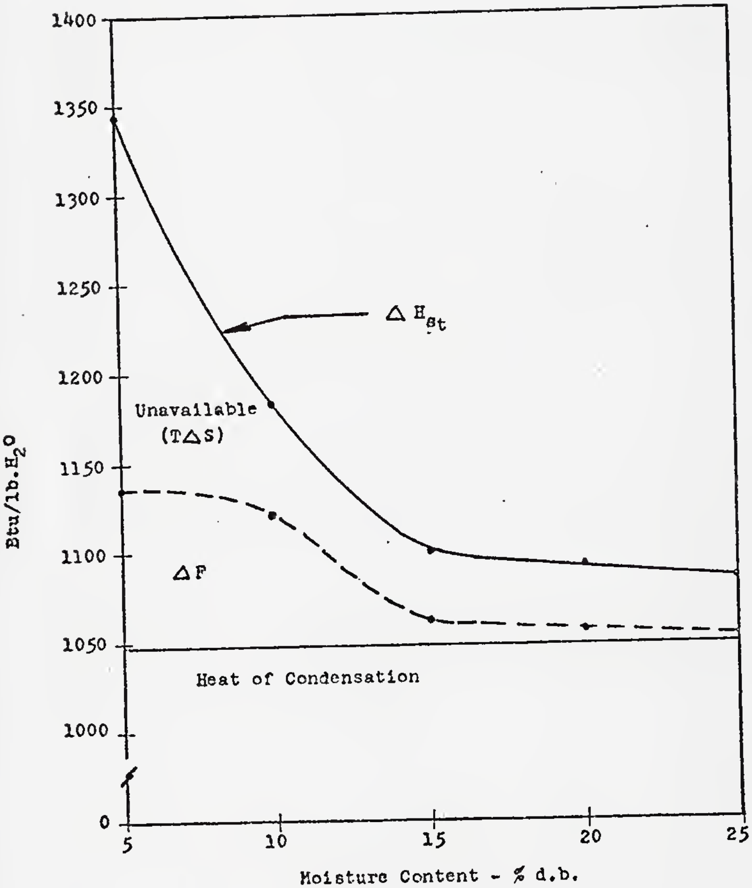


Figure 11. Isosteric heat of adsorption (ΔH_st) for corncobs at 81° F, as composed by the heat of condensation, change in free energy, and change in unavailable energy.

account environmental conditions at which dry corncobs are to be stored, and their application as a desiccant for static adsorption.

Table 10 shows the 3-sample average of the moisture content of whole, ground, and chopped corncobs, as it changed after placing the samples in the environmental chamber at 80°F and 85% relative humidity. Data for other cases are given in tables A-1 through A-10 of the appendix. Data for replications that were considered unreliable due to unstable chamber conditions or any other reason are not included in this thesis.

Table 10. Average moisture contents (% d.b.) for ground, whole, and chopped corncobs adsorbing moisture at 80°F and 85% relative humidity.

TIME	MOISTURE CONTENT - % d.b.		
(Hrs)	GROUND	WHOLE	CHOPPED
Initial	5.43	6.33	6.20
6	13.04	12.11	11.11
25.5	17.66	16.59	15.66
47	18.36	17.78	17.51
73	18.63	18.30	18.17
98	18.97	18.75	18.88
127	18.89	18.79	18.98
145	18.77	18.72	18.91

Figure 12 is a plot of the data in Table 10 showing the general shape of the moisture adsorption curves. Ground corncobs have the highest moisture adsorption rates in at least the first 48 hours, or before their moisture content approaches equilibrium and tends to level off. In eleven out of fourteen tests, whole cobs showed higher moisture adsorption rates than chopped corncobs. Normally chopped cobs would have a greater surface area per unit weight, which is likely to result in higher adsorption rates. The results suggest, however, that an unknown factor affected their moisture adsorption rates, perhaps the way samples were piled in baskets, or having cut the cobs with a rotary blade saw.

In general, the asymptotic equilibrium moisture content for whole, ground, and chopped cobs was approximately the same, but in a few occasions chopped corncobs reached a slightly higher E.M.C. It is also seen that when the moisture content of the corncobs is near equilibrium some fluctuations occur. Table 11 gives the values of the average asymptotic moisture contents for ground, whole, and chopped cobs, and those predicted from the isotherm equations. The isotherm equations predict a slightly higher value for the equilibrium moisture content in most cases, as it can be expected since samples used for isotherm determinations were allowed to adsorb moisture for approximately one more week. However, the greatest difference found is 1.3% moisture content, and in most cases the predicted and asymptotic values agree within ± 0.5% moisture content.

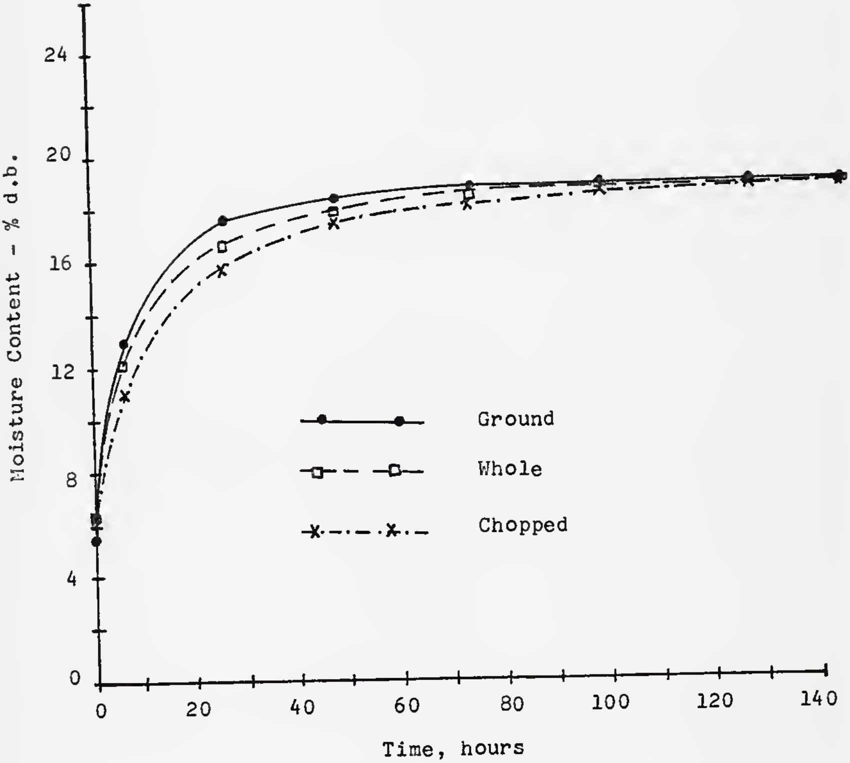


Figure 12. Average moisture content for ground, whole, and chopped corncobs adsorbing moisture at 80°F and 85% relative humidity versus adsorption time.

Table 11. Equilibrium moisture content predicted from isotherm equations and average experimental asymptotic EMC for ground, whole and chopped corncobs at different environmental conditions.

CONDITIONS	PREDICTED	ASYMPTOTIC		
		Ground	Whole	Chopped
72°F, 86% R.H.	20.5%	19.2%	19.3%	20.2%
72°F, 61% R.H.	10.8%	10.7%	10.9%	10.7%
80°F, 85% R.H.	19.1%	18.8%	18.7%	18.9%
80°F, 61% R.H.	10.4%	10.5%	10.8%	10.9%
90°F, 83% R.H.	17.2%	16.7%	16.7%	17.1%
90°F, 60% R.H.	9.94%	9.51%	9.62%	9.86%

Several models were used in trying to develop an expression which could describe the average moisture content ($\overline{M}_t$) at any time (t). Among those that did not prove successful are:

$$\frac{\overline{M}_t - M_o}{M_e - M_o} = \exp\ (kt) \qquad (21)$$

$$M_t = M_e\ (1 - e^{-kt}) \qquad (22)$$

$$\frac{d\overline{M}}{dt} = A \exp\ (-b\ (\overline{M}_t - M_o)) \qquad (23)$$

where t is time in hours, M_e is equilibrium moisture content, M_o is initial moisture content, and A, b and k are constants.

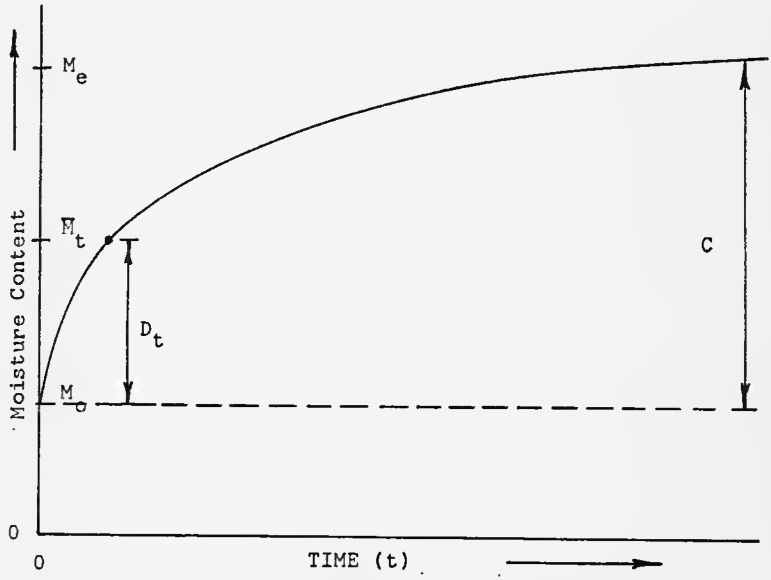


Figure 13. General shape of the moisture content vs. time curve for corncobs during static adsorption.

From Figure 13 it can be seen that the moisture content at any time (M_t) is equal to $M_o + D_t$, but the amount D_t seems to be equal to C times a decreasing exponential function of time. Based on the above, the following model was developed to describe M_t:

$$M_t = M_o + C \exp(-k/t) \tag{24}$$

where t is time in hours, and C and k are constant. At the beginning of the adsorption process t is equal to zero, and exp (-k/t) tends to go to zero, thus satisfying the boundary condition $\overline{M}_t = M_o$ at t=0. As the adsorption process continues and t becomes larger and larger, exp (-k/t) approaches 1, and $M_t = M_o + C$, satisfying the second boundary condition $M_t = M_e$ at equilibrium.

The linearlized form of equation (24) is:

$$\ln(M_t - M_o) = \ln C - k/t \tag{25}$$

A plot of ln $(M_t - M_o)$ against 1/t yields a straight line as shown in Figure 14 for data taken on whole corncobs at 90°F and 83% relative humidity. Straight lines are also obtained for ground and chopped corncobs at all other environmental conditions. The constant C in equation (24) can be obtained by raising the base of the natural logarithm (e) to a power with numerical value equal to the intercept of the straight line, and the constant k is equal to the slope of the straight line.

A computer program that performs a least squares method was utilized to find the constants C and k for ground, whole, and chopped corncobs with different initial moisture contents and adsorbing moisture in different environments. The results are shown in Table 12.

The R^2 value multiplied by 100 is the percent of variation

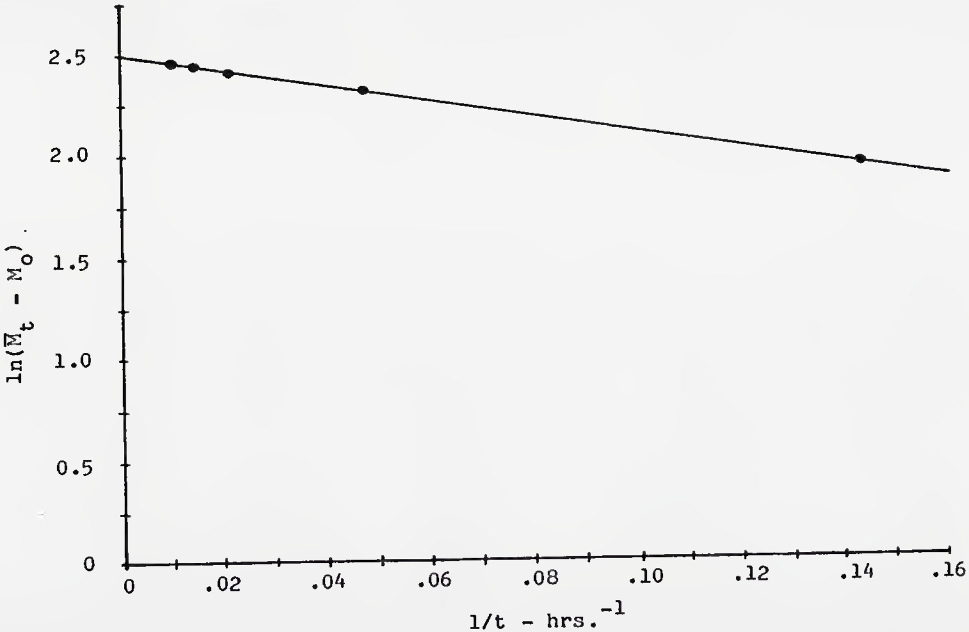


Figure 14. Plot of the left-hand side of equation (25) vs. 1/t for whole corncob adsorption data at 90°F and 83% relative humidity.

Table 12. Constants in adsorption equation (24) for whole, ground, and chopped corncobs at different environments and initial moisture contents.

Temperature	R.H.	M_o	C	k	R^{2*}
		GROUND CORNCOBS			
72°F	86%	1.17%	18.63	5.209	0.997
72°F	86%	3.62%	15.91	6.670	0.995
72°F	61%	5.13%	5.605	3.329	0.988
80°F	85%	5.43%	13.94	3.617	0.999
80°F	61%	5.56%	5.132	1.322	0.990
90°F	83%	5.04%	11.85	2.227	0.999
90°F	60%	5.46%	3.838	1.299	0.998
		WHOLE CORNCOBS			
72°F	86%	1.24%	19.25	10.80	0.995
72°F	86%	3.51%	16.52	12.10	0.978
72°F	61%	6.20%	4.812	6.512	0.999
80°F	85%	6.33%	12.78	4.801	0.996
80°F	61%	6.62%	4.427	3.453	0.995
90°F	83%	4.95%	12.11	3.781	0.998
90°F	60%	6.01%	3.525	2.569	0.999

Table 12. (cont.)

		CHOPPED CORNCOBS			
Temperature	R.H.	M_o	C	K	R^{2*}
72°F	86%	1.41%	20.0	9.144	0.998
72°F	86%	3.33%	17.39	8.341	0.985
72°F	61%	5.65%	5.326	6.557	0.998
80°F	85%	6.20%	12.95	5.917	0.986
80°F	61%	6.32%	4.843	4.136	0.986
90°F	83%	5.17%	12.34	4.393	0.995
90°F	60%	6.32%	3.483	2.418	0.999

* R^2 X 100 = % of variation about the mean that is explained by the linear model.

about the mean that is explained by the linear model. Values of R^2 given in Table 12 are all higher than 97%, and in some cases they are up to 99.9%, demonstrating the adequacy of equation (24) to calculate the moisture content of corncobs at any time for the adsorption tests carried out. Figure 15 shows the predicted moisture content from equation (24) at any time t, and the experimental values obtained at 72°F and 86% for whole corncobs.

Equation (24) is considered to apply better when the time t is not less than 5 hours, and has a practical upper limit of about 360 hours (15 days). The derivative of equation (24)

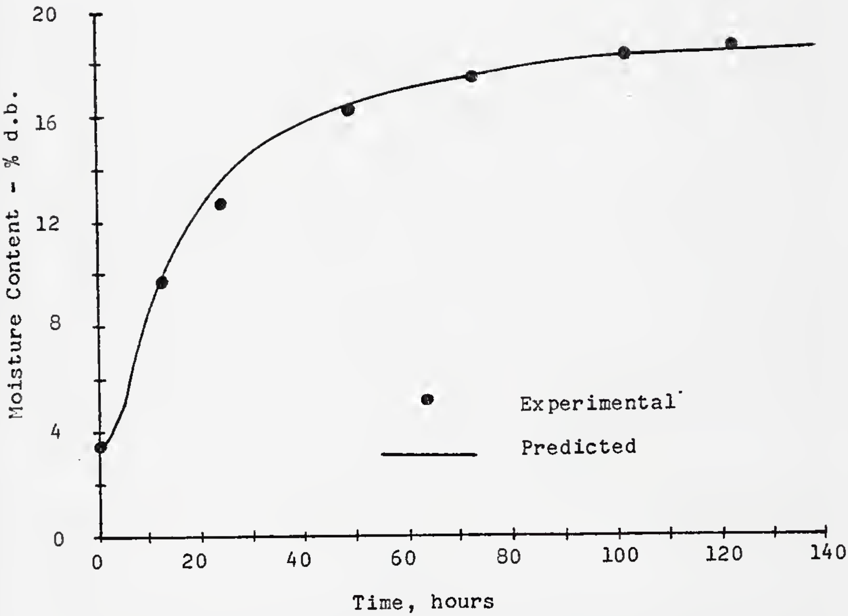


Figure 15. Experimental and predicted moisture contents for whole corncobs adsorbing moisture at 72°F and 86% relative humidity.

gives the rate at which the moisture content of the corncobs is changing at a particular time t. Differentiating equation (24) and rearranging some terms the folowing equation is obtained:

$$\frac{d\overline{M}}{dt} = C_1 \frac{\exp(-k/t)}{t^2} \tag{26}$$

where C_1 is equal to the product Ck. Substituting the values for C and k used for Figure 15, the moisture content after 360 hours (15 days) would be changing at the rate of 0.0015% per hour or 0.036% per day, which from a practical point of view is negligible.

Figure 13 shows that the constant C in equation (24) can be defined as $(M_e - M_o)$. If the values for C obtained by the computer analysis are indeed equal to $(M_e - M_o)$ where M_e is obtained from the isotherms, only the value of k in equation (24) would have to be evaluated in order to find $\overline{M}_t$, and the general model can be simplified. Figure 16 shows a plot of constant C against $(M_e - M_o)$ and the deviation from a 45° straight line for ground, whole, and chopped corncobs. It can be observed that the deviation is not very large in any case, and thus it can be said that $C = (M_e - M_o)$. Equation (24) then becomes:

$$\frac{M_t - M_o}{M_e - M_o} = e^{-k/t} \tag{27}$$

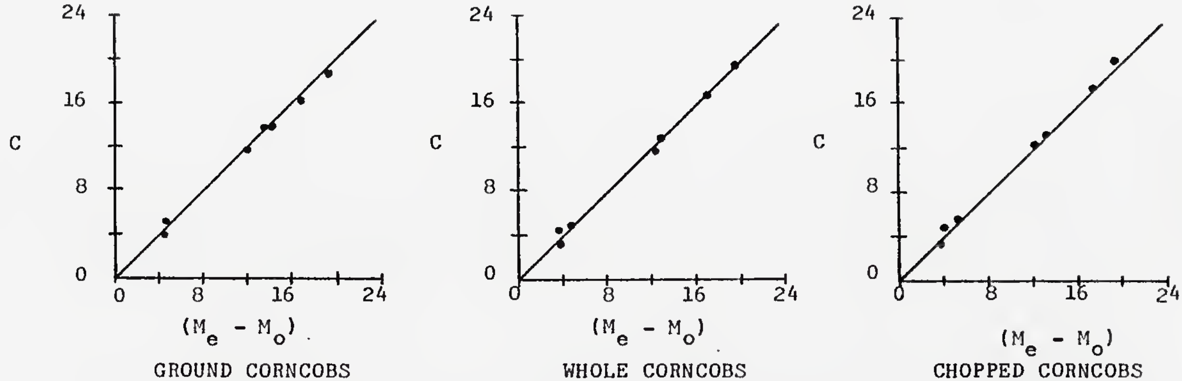


Figure 16. Plot of constant C against $(M_e - M_o)$ for ground, whole, and chopped corncobs, showing deviation from a 45° straight line. Constant C was obtained from computer analysis, and M_e from predicted isotherms.

where the left-hand side is called the moisture ratio MR. The linearized form of equation (27) is:

$$\ln MR = -k/t \tag{28}$$

A computer program that performs a least squares method on an equation of the same type as (28) was utilized to calculate the constant k using adsorption data. A constant for adsorption at 80°F and 61% relative humidity was not calcuated since $\overline{M}_t$ reached a higher value than M_e at about 24 hours. Results from the computer analysis are given in Table 13.

The R^2 values from Table 13 are all higher than 0.920, except the one for ground corncobs at 90°F and 83% R.H., which for an unknown reason resulted much lower than the rest. Equation (27) is considered adequate to describe the moisture content or Moisture Ratio of corncobs adsorbing moisture in different environments. Figure 17 shows the predicted moisture content from equation (27) at any time t, and the experimental values obtained for whole cobs at 80°F and 85% relative humidity. The same graphs are shown in Figures A.1 throught A.6 of the appendix for ground, whole, and chopped corncobs.

The rate at which the moisture content M_t is changing at any time t is given in equation (26), where $C_1 = (M_e - M_o)k$, and the values of k are obtained from Table 13.

The model for moisture adsorption can be generalized if a relationship is found that describes k in terms of known parameters. Empirical models describing k as a function of

Table 13. Results of the computer analysis on equation (28) from data for whole, ground, and chopped corncobs adsorbing moisture at different environments, and with different initial moisture contents.

Temperature	R.H.	M_o	k	R^2
		WHOLE CORNCOBS		
72°F	86%	3.51	12.64	0.988
72°F	86%	1.24	10.90	0.998
72°F	61%	6.20	5.664	0.974
80°F	85%	6.33	4.793	0.998
90°F	83%	4.95	3.937	0.997
90°F	60%	6.01	3.296	0.925
		GROUND CORNCOBS		
72°F	86%	1.17	5.913	0.986
72°F	86%	3.62	7.807	0.978
72°F	61%	5.13	3.543	0.990
80°F	85%	5.43	3.457	0.996
90°F	83%	5.04	2.525	0.983
90°F	60%	5.46	2.332	0.754
		CHOPPED CORNCOBS		
72°F	86%	1.41	8.235	0.988
72°F	86%	3.33	8.081	0.991
72°F	61%	5.65	5.913	0.984
80°F	85%	6.20	5.884	0.991
90°F	83%	5.17	4.183	0.994
90°F	60%	6.32	2.677	0.984

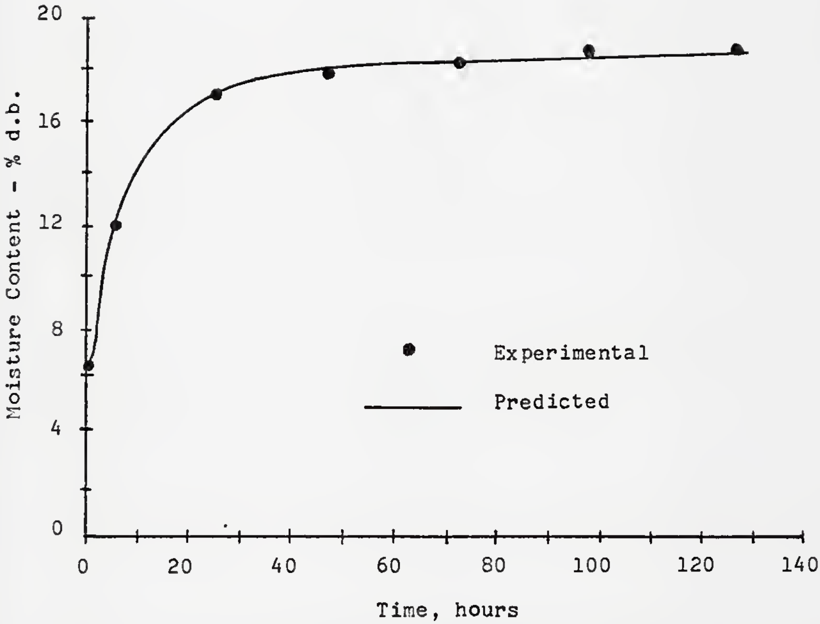


Figure 17. Predicted and experimental values of the moisture content of whole corncobs adsorbing moisture at 80°F and 85% relative humidity.

temperature, relative humidity, and initial moisture content, including all possible combinations did not prove successful. A model describing k in terms of the difference between the partial pressures inside the corncobs at M_e and M_o did not show encouraging results. Finally, a model that describes k in terms of the partial pressure inside the cobs at the initial moisture content M_o was chosen. The partial pressure at M_o was estimated by calculating the equilibrium relative humidity corresponding to M_o at the test temperature. The model chosen is of the form:

$$k = \exp\left(a + bP_{M_o}\right) \tag{29}$$

where a and b are constants, and P_{M_o} is the partial pressure inside the corncobs at the initial moisture content, as estimated from the isotherm at the test temperature. The partial pressure at M_e is taken into account indirectly in model (27) since in order to find M_e the relative humidity of the environment in which the cobs are placed has to be known. The linearized form of equation (29) is:

$$\ln K = a + b\left(P_{M_o}\right) \tag{30}$$

The constants a and b obtained from a least squares computer analysis and the R^2 value of the corresponding model are given in Table 14.

Table 14. Constants a and b in equation (29) and R^2 value of model (30) for whole, ground, and chopped corncobs.

Corncob Form	a	b	R^2
Whole	2.687	-7.465	0.908
Ground	2.018	-6.259	0.763
Chopped	2.227	-4.749	0.899

Model (29) does not predict k very accurately as it can be seen from the R^2 value of each linear model, but provides a means to approximate the value of constant k for the static adsorption case. The constant is thought to include geometric properties of the adsorbing material, as well as its diffusivity.

In summary, Model (27) has shown to describe well the moisture content of corncobs at any time during static adsorption. The model is believed to also apply for the dynamic adsorption case by modifying the constant k to include the effect of airflow.

D. Effect of Drying Temperature on Equilibrium Moisture Content After Rewetting

It was originally believed that drying the corncobs at relatively high temperatures could result in cracks, or alteration of the corncobs' structure, as to make a difference in the equilibrium moisture content after allowing the corncobs to

regain moisture.

Corncob samples were dried at 95°F, 140°F, and 180°F and then placed in the environmental chamber at 72°F and 86% relative humidity to investigate if any difference in the final equilibrium moisture content occurred. Table 15 gives the values of the initial and final moisture contents for ground, whole, and chopped corncobs dried at the three temperatures.

Table 15. Average initial and final moisture contents for corncobs dried at different temperatures and placed in a 72°F and 86% relative humidity environment.*

Form of Corncobs	Drying Temperature	Initial M.C. % d.b.	Final M.C. % d.b.
	95°F	3.62	19.0
GROUND	140°F	1.17	19.2
	180°F	0.424	19.4
	95°F	3.51	19.3
WHOLE	140°F	1.24	19.4
	180°F	0.555	19.3
	95°F	3.33	20.2
CHOPPED	140°F	1.41	20.3
	180°F	0.498	20.2

* Initial M. C. refers to the moisture content of the cobs after drying, and Final is the equilibrium moisture content after adsorption.

Obviously, the moisture content that the samples reached after the drying period decreased with increasing drying temperature as indicated in Table 15. By looking at the results for ground corncobs alone it could be said that there is a minor effect of the drying temperature on the equilibrium moisture content attained after rewetting. However, when examining all the results shown in Table 15 it is concluded that there is no effect of drying temperature on the final equilibrium moisture content.

The above conclusion does not mean however, that cracks are not developed when drying at high temperatures, and it is possible that very high drying temperatures could result in structural changes within the corncobs which in turn could affect the equilibrium moisture content. The conclusion given for the experiment only applies for the range of temperatures tested.

E. Cyclic Performance

To investigate the effect of successive wetting and drying cycles on the adsorptive capacity of corncobs, ground and whole cobs were placed in the environmental chamber at 81°F and 79% relative humidity where three successive adsorption cycles were performed. Drying after the first and second cycles was done in the laboratory ovens at 151°F (66°C) for 20 hours. Table 16 shows the average final moisture content after each adsorption cycle, and the percent change in the final moisture content with respect to the first run.

Table 16. Average final moisture contents after three adsorption cycles at 81°F and 79% R. H. indicating the percent change with respect to cycle 1.

WHOLE CORNCOBS			GROUND CORNCOBS		
Cycle #	Final M.C.	% Change	Cycle #	Final M.C.	% Change
1	15.66		1	15.14	
2	15.32	-2.17	2	15.09	-0.330
3	15.09	-3.63	3	14.99	-0.990

The results shown in Table 16 could suggest that a small reduction in the final adsorptive capacity results with successive drying and wetting cycles. However, it has to be noted that the bone-dry weight was not obtained until after the third wetting cycle, and any material lost during the successive handling would appear as a reduction in the adsorptive capacity. Furthermore, the percent decrease of the moisture content for ground corncobs is almost negligible.

Therefore, it is concluded that successive wetting and drying cycles do not appear to affect the corncobs' adsorptive capacity. Tests run for Part II of the study confirmed the above conclusion.

PART II

A. Grain Conditioning Experiments

As indicated in the Materials, Procedures, and Equipment section, a total of five experiments were carried out for Part II of the study. They involved both natural and forced-air conditioning systems for corn at various initial moisture contents as shown in Table 4. Corncobs were placed in separate insulated chambers adjacent to the corn bins, and warm, humid air was drawn from an environmental chamber kept at approximately 80°F and 83% relative humidity.

The constant environmental conditions inside the chamber were selected to simplify and reduce the number of experiments, and to provide an environment which would make grain conditioning and drying virtually impossible without a means to reduce the relative humidity of the air. A good performance of the system with the selected environmental conditions will practically assure its success in a less harsh environment. The above conditions are thought to be representative of average climates prevailing in some areas in tropical countries.

Since no basis existed for deciding what was the appropriate corn to corncob ratio to use, constant volume corncob chambers were built in order to simplify the experiments and provide a fairly large corn to corncob weight ratio, but avoiding an excessive corncob volume when compared to the volume of the corn storage bin. The corn to corncob weight ratio was

approximately 29 to 1 in the majority of cases, and the bin to chamber net volume ratio was 6.0 to 1.

Figure 18 shows typical curves for three different airflows and corncob initial moisture contents that indicate the value of the relative humidity of the air leaving the corncob chamber (or entering the corn bin) from the time the cobs are put in place. Airflows of 1.6, 1.0, and 0.5 cfm per lb. of corncobs correspond to approximately 3.2, 2.0, and 1.0 cfm per bushel of corn respectively. It is seen that both the airflow and the initial moisture content of the corncobs affect the value of the relative humidity of the air leaving the cob chamber. The higher the air flow rate the sooner the corncobs have to be replaced, and the higher the initial corncobs' moisture content the lower the adsorption rate. As indicated in the Materials, Procedure, and Equipment section, the corncobs were replaced when the relative humidity of the air entering the corn bin reached about 72% to 78%. This occurred about every 12 hours for an airflow of 3 cfm per bushel of corn, every 12 to 24 hours for an airflow of 2 cfm per bushel, and 48 hours or longer for a very low airflow and natural ventilation experiments.

The relative humidity of the air on the exit side of the corncob chamber decreases almost instantly when the corncobs are put in place. As shown in Figure 18, a few minutes after the humid air has passed through a corncob chamber filled with dry cobs, the relative humidity of the air leaving the chamber drops to 35 or 40%. During the initial part of the process, the

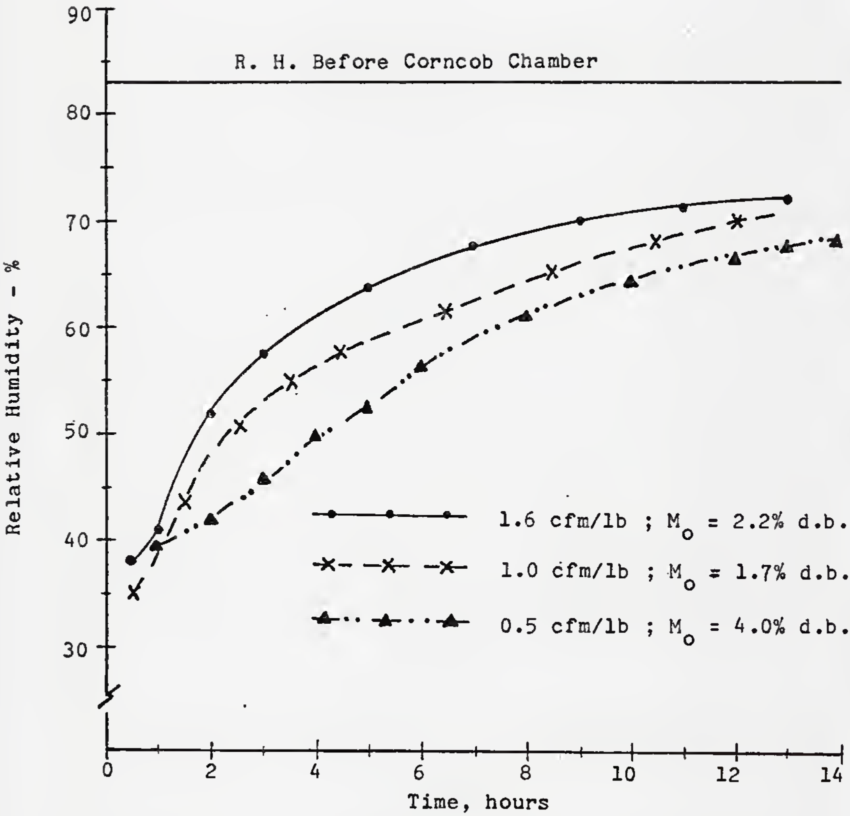


Figure 18. Relative humidity of air leaving the corncob chamber at three different airflows and for different initial moisture contents of the cobs.

corncobs are at a very low moisture content and the heat generated is capable of increasing the air temperature up to 20°F (11°C) for a few minutes. The reduction in the relative humidity of the exiting air is partly due to the above increase in temperature. Figure 19 shows the recorded dry bulb air temperatures at the inlet and exit of the corncob chamber for a batch of corncobs at an initial moisture content of 1.6% d.b., with air flowing at the rate of 1 cfm/lb. of cobs (2 cfm/bu. of corn) during experiment No. 5. Similar patterns occur for other air flow rates and initial moisture contents.

Except for the first hour at the beginning of the adsorption process, the wet bulb temperature of the air at the corncob chamber outlet is approximately the same as that before the cob chamber. The above indicates that most of the moisture adsorption process follows a wet bulb line as it is theoretically assumed.

The moisture content of the corncobs after 12 hours of adsorption was not always in equilibrium with the relative humidity of the air at the corncob chamber outlet. The final moisture content of the cobs at the point of regeneration ranged from about 8 to 12% d.b. for the forced-air experiments, and from 5 to 13% d.b. for the natural ventilation experiments.

As it was pointed out before, a total of five experiments were carried out for Part II of the study. Each experiment will be now discussed separately.

B. Experiment No. 1

Yellow dent corn was harvested on a local farm at a

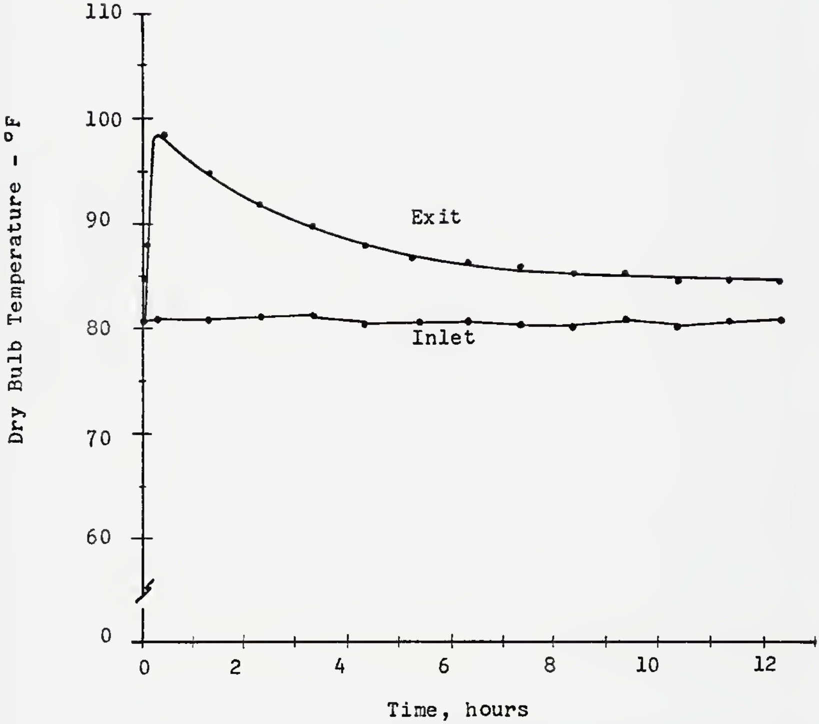


Figure 19. Dry bulb air temperatures at the inlet and exit of the corncob chamber for a batch of corncobs at 1.6% d.b. initial moisture content with an airflow rate of 1 cfm/lb. of cobs.

moisture content of 25% w.b., and passed through the Clipper cleaner. All the corn was placed in sacks which stood in the shop overnight before the corn was transferred to the bins. It will be seen later how this period of time was crucial in the development of fungi, contributing to the apparent failure of the system.

About 8 bushels of corn (450 lbs.) were placed in one bin (Bin No. 1), and the fan was adjusted to deliver 24 cfm or about 3 cfm per bushel of corn. Corncobs were regenerated approximately every 12 hours for this case.

Approximately 6 bushels of corn (350 lbs.) were placed in another bin (Bin No. 2) for a natural ventialation experiment. The room fan was set to simulate approximatley a 5.5 mph wind (8.8 kmph) at the roof turbine, which created little air movement through the corncobs and the corn mass. The airflow was measured to be 0.11 cfm/bu. of corn, although the difficulty and errors involved in detecting such low air flows should not be neglected. It was found later that part of the perforated floor in the bin had been plugged with some corn fines. Regeneration time for the corncobs varied from 24 to 48 hours.

Table 17 shows the corn moisture content during the forced-air experiment for the four layers sampled within the bin. Outer and center samples were averaged for each layer. The moisture content in the outer zone showed to be a little lower in most cases, indicating non-uniformity of airflow through the bin. As shown in Table 17, the bottom layer of the bin dried down to

15.1% w.b. in six days, while the corn at other levels dried only to an average of 21.5%. The data suggests that a higher airflow rate is necessary for conditioning corn at 25% moisture content.

Table 17. Average moisture content of corn at four different layers during experiment No. 1 with an airflow of 3 cfm/bu.

TIME	AVERAGE MOISTURE CONTENT - % w.b.			
	Top	Upper	Lower	Bottom
Initial	24.8	25.2	24.1	24.7
16 hrs	24.0	24.3	23.7	24.2
41 hrs	23.3	23.5	23.3	22.7
73 hrs	23.1	23.5	23.0	20.4
97 hrs	22.2	22.3	21.4	17.2
120 hrs	22.0	22.1	21.0	16.0
144 hrs (6 days)	21.7	21.9	21.0	15.1

The experiment was stopped since excessive mold contamination resulted by the sixth day. Table 18 shows the percent of kernels infected with Aspergillus Flavus, Aspergillus Niger, and Penicillium, based on the average for the entire bin.

Table 18. Percent of kernels infected with 3 kinds of fungi during experiment No. 1 with an airflow rate of 3 cfm/bu.*

TIME	PERCENT OF KERNELS INFECTED		
	A. FLAVUS	A. NIGER	PENICILLIUM
Initially	8	3	35
3 Days	31	4	68
6 Days	31	5	68

* Average for entire bin.

It is observed that the corn contained initially a fairly high percentage of infected kernels, especially Penicillium spores. Having let the corn stand overnight is thought to be the cause for a high initial storage fungi contamination. The rapid growth of storage fungi is not surprising since the spores initially in the corn were provided with optimum growth conditions, as are high moisture content and warm temperature. Most of the growth seemed to occur between the time grain was put in the bin and the third day. Aspergillus flavus contamination was higher in the upper and top layers of the bin, while the distribution of A. Niger and Penicillium was more or less uniform throughout. The percentage of kernels invaded with field fungi such as Alternaria and Cladosporium was reduced at the time the experiment was terminated.

The natural ventilation experiment did not show very

encouraging results with a simulated 5.5 mph wind and 25% initial moisture content corn. After 6 days the moisture content at the top layer was about 24% w.b., 22.8% at the middle, and 20.7% at the bottom of the bin. The daily average moisture content values for all layers sampled are given in Table A.11 of the appendix. Table 19 shows the percentage of kernels infected with 3 kinds of fungi as the average for the entire bin.

Table 19. Percent of kernels infected with 3 kinds of fungi during the natural ventilation case of experiment No. 1.*

TIME	PERCENT OF KERNELS INFECTED		
	A. FLAVUS	A. NIGER	PENCILLIUM
Initially	8	3	35
3 Days	29	3	34
6 Days	38	7	65

* Average of entire bin.

Unlike the forced-air case where not appreciable mold growth occurred between the third and sixth day, Table 19 indicates that there was a considerable increase in mold infestation between the third and the sixth day for the natural ventilation case, and it would have probably continued if the experiment had not been terminated. It is concluded that higher wind speeds are required for the natural ventilation system when

conditioning high moisture corn. The facts that there were initially many kernels already infested when the experiment was started, and that part of the perforated floor was plugged with grain fines, are also considered as major reasons that explain the unsatisfactory results for experiment No. 1.

C. Experiment No. 2

Corn utilized for experiment No. 2 was harvested on a local farm, passed through the Clipper cleaner, and placed in the bins, all in the same day. The average moisture content was 16% w.b.

A total of 450 lbs. (8 bushels) of corn were placed in bin #1 for a forced-air experiment. The fan was set to deliver 3 cfm/bu. Corncobs were regenerated about every 12 hours for this test.

About 6 bushels of corn were placed in bin #2 for a natural ventilation trial with a simulated wind of about 7.5 mph (12 kmph) on the roof turbine of bin #2. The air velocity inside the duct before and after the corncob chamber was very low to be measured accurately with the hot wire anemometer, thus it is unknown what the airflow was for the natural ventilation case. Corncobs were replaced twice during this test.

Figure 20 shows the average moisture content of the center and outer zones for the top, lower, and bottom layers of the bin utilized for the forced-air experiment. A fairly uniform airflow was obtained, as concluded from the moisture content

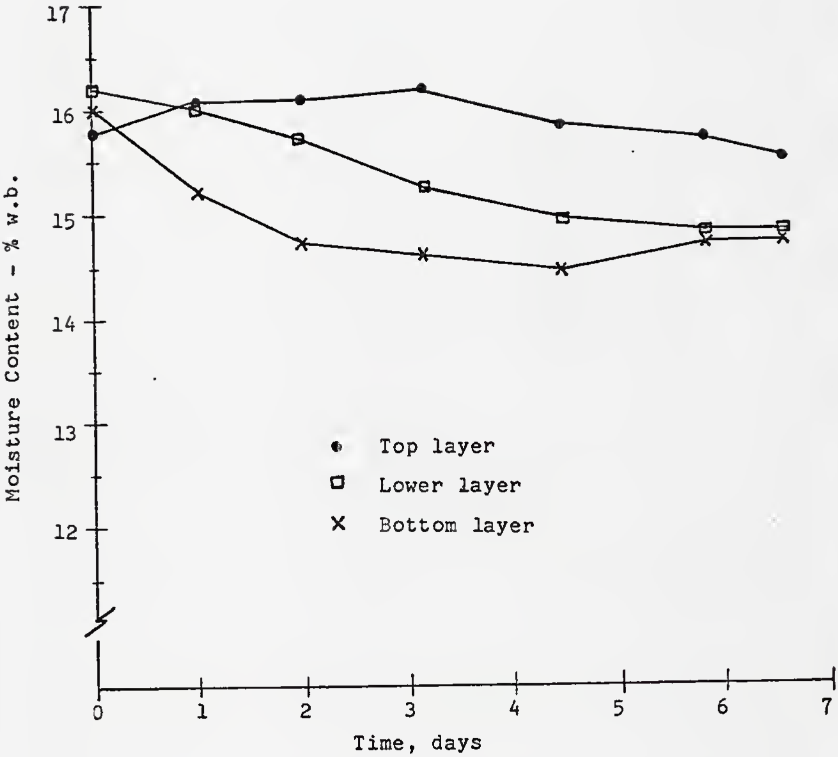


Figure 20. Average moisture content at the top, lower, and bottom layers of the bin with an airflow of 3 cfm/bu. in experiment No.2.

of the center and outer zones. Moisture contents at all layers are given in Table A.12 of the appendix. The moisture content of the upper layer was in between those of the lower and top layers. The moisture content at the bottom and lower layers reached about 14.6% by the seventh day. The percent of moisture in the bottom layer decreased rapidly, while that in the top of the bin increased at the beginning of the experiment due to moisture driven up from lower layers.

A total of 230 lbs. of corncobs (15 batches) were used during the course of this test. This represents approximately 2.0 pounds of corn dried for each pound of corncobs used.

Table 20 shows mold contamination data for the forced-air experiment. The percent of infestation by the fungi shown was more or less uniform throughout the bin, thus the values given represent the average for the entire bin.

Table 20. Fungi contamination for experiment No. 2 with corn at 16% w.b. initial moisture content and an airflow of 3 cfm/bu.

DAY	A. FLAVUS	A.NIGER	PENICILLIUM	FUSARIUM	ALTERNARIA*
Initial	0%	0%	41%	56%	5%
4	0%	0.5%	33%	54%	8%

* Combined with Trichoderma and Nigrospora.

No Aspergillus Flavus contamination was detected, perhaps due to the low moisture content of the grain. The percent increase in A. Niger can be considered almost negligible, and it is observed that the percent of Penicillium and Fusarium decreased. Christensen (1974) states that Alternaria, a field fungi, is almost always detected when plating freshly harvested kernels, and that a decrease in Alternaria growth during storage can constitute biological evidence that the kernels are undergoing deterioration.

Therefore, it is concluded that no kernel deterioration occurred during the week that the forced-air experiment was allowed to run. It is estimated that at the end of the tenth day the entire bin would have reached a moisture content of approximately 14.0 to 14.5% without grain deterioration. In order to dry the grain down to 13% moisture content the average relative humidity entering the bin should be decreased, suggesting a shorter regeneration time for the corncobs which is probably impractical. By reducing the airflow a decrease in the average relative humidity entering the bin could be obtained, but the drying time would be longer.

Results from the natural ventilation test for bin No. 2 are not considered very reliable since contrary to what was expected, the top layer dried faster than the center and bottom layers. Although care was taken to seal the bin roof, it seems that some air leakage occurred at the bin's eave, causing room air to pass over the top layer before being

exhausted back to the room, thus contributing to dry the top layer.

The final moisture contents at the top, center, and bottom layers were 13.3, 14.9, and 14.6% w.b. respectively. The moisture contents at the three layers throughout the test are given in Table A.13 of the appendix. The total corn to corncob ratio used during this experiment was 11.6 to 1.

Mold infestation in the corn with natural ventilation was almost the same as that for the forced-air test, as shown in Table 20, except that no increase in A. Niger was detected. Corn from the two bins was entirely sound for feed after the experiment was terminated.

D. Experiment No. 3

Corn utilized for this experiment was harvested in southern Nebraska at about 23% moisture content and brought to Manhattan by truck. The corn remained overnight in the tarpaulined truck when the average outside temperature was 56°F. The grain was cleaned the next day and placed in the bins.

The experiment consisted of two forced-air tests with airflows of 2 and 3 cfm per bushel of corn. A total of 450 lbs. (about 8 bushels) were placed in each bin. Corncobs were changed approximately every 12 hours in both cases.

Figure 21 shows the average moisture content for the center and outer zones at the top, lower, and bottom layers of the bin with an airflow of 2 cfm/bu. The moisture content at the upper

layer was in between those of the top and lower layers. Table A.14 in the appendix gives the moisture contents at all four layers during this experiment. Generally, the moisture content around the central zone was slightly lower than that around the outer zone, indicating that the airflow was not exactly uniform across the bin. The moisture content in the bottom layer was 13.5% when the test was terminated. A total of 1.3 pounds of corn was dried for each pound of corncobs used during this test.

Table 21 shows the mold counts for the top and bottom halves of the bin with an airflow of 2 cfm/bu.

Table 21. Mold contamination in the top and bottom halves of the bin for the 2 cfm/bu. test in experiment No. 3.*

TIME	LOCATION	A.FLAVUS	FUSARIUM	PENICILLIUM	ALTERNARIA
Initial	Entire Bin	0%	46%	1%	5%
7 Days	Top ½	5%	95%	64%	25%
	Bottom ½	14%	98%	51%	18%
13 Days	Top ½	10%	93%	94%	14%
	Bottom ½	8%	96%	65%	27%

* % of plated kernels with specified fungi.

On the average, Aspergillus flavus increased from 0 to 9%.

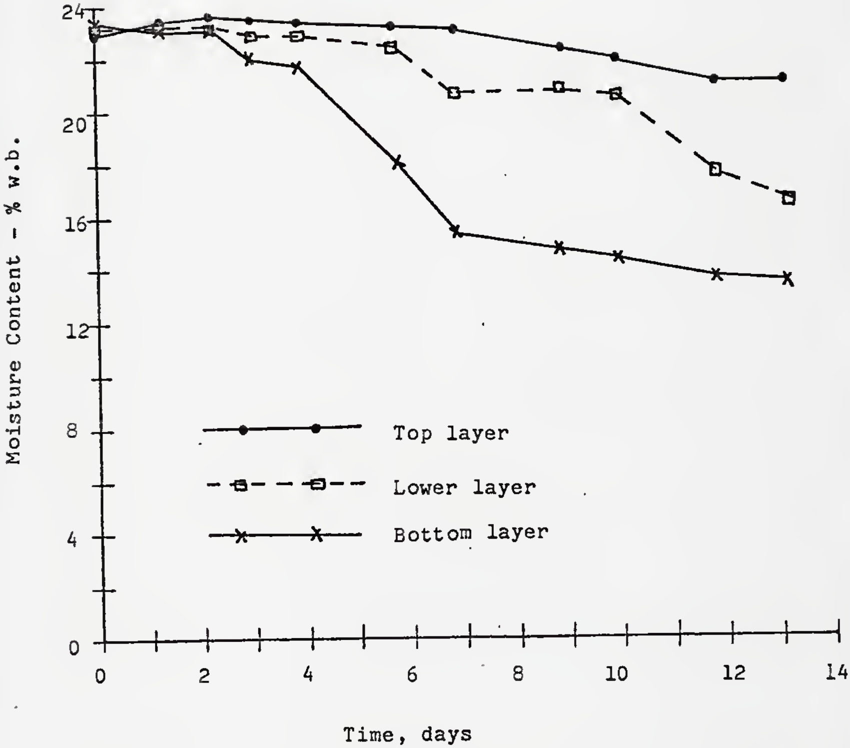


Figure 21. Average moisture content at the top, lower, and bottom layers of the bin with an airflow of 2 cfm/bu. in experiment No. 3.

The corn already contained 46% Fusarium, a field fungi, when the test was started, and rapidly increased to an average of 95%. Some species of Fusarium can be toxic. The mold analysis also showed a high percentage of Penicillium in the top half of the bin when the test was terminated. The percentage of Alternaria, another field fungi, increased from 5% to 27% at the bottom of the bin, indicating that the corn at the very bottom layer was in good condition. The above was verified when the bin was emptied.

Figure 22 shows the moisture content at all four layers during the test with an airflow of 3 cfm/bu. The final moisture content at the bottom layer was 13.7%, and all layers show faster initial drying rates than those of the test utilizing an airflow of 2 cfm/bu. The average moisture content of the lower two thirds of the bin was 14.4% w.b. at the end of the thirteenth day, an 8.8% moisture content decrease from the average initial moisture content. 1.2 pounds of corn were dried for each pound of corncobs used during this test.

The moisture content at the bottom layer of this test seems to be decreasing at a slower rate than that of the test at 2 cfm/bu. at the end of the thirteenth day. Moreover, the mois-content at the bottom layer of the bin with the lower airflow was slightly lower when the experiment terminated. Thus, it is concluded that lowering the airflow decreases somewhat the average relative humidity entering the bin. The equilibrium relative humidity of 13.5% w.b. corn for desorption at 25°C is approximately 65%, which gives us an indication of the average

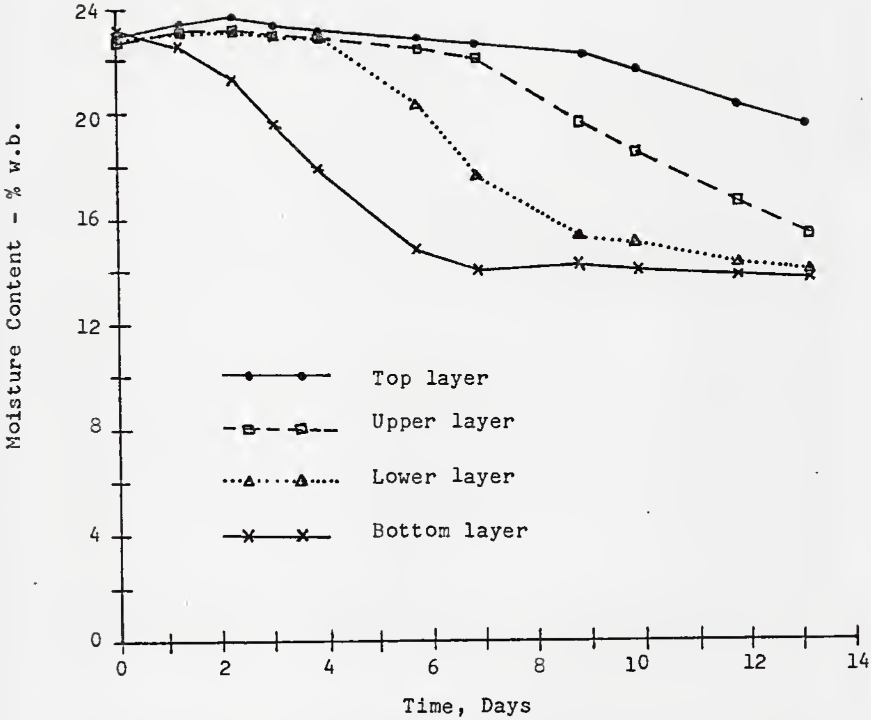


Figure 22. Average moisture content at the top, upper, lower, and bottom layers of the bin with an airflow of 3 cfm/bu. in experiment No.3.

relative humidity entering the bins over the 12-hour adsorption period. This represents approximately an average relative humidity decrease of 12 to 18% from that inside the environmental chamber.

Table 22 shows the mold counts for the top and bottom halves of the bin. Only a 2% A. Flavus infestation was found in

Table 22. Mold counts in the top and bottom halves of the bin with an airflow of 3 cfm/bu.*

TIME	LOCATION	A.FLAVUS	FUSARIUM	PENICILLIUM	ALTERNARIA
Initial	Entire Bin	0%	46%	1%	5%
7 Days	Top ½	13%	94%	56%	12%
	Bottom ½	2%	86%	25%	26%
13 Days	Top ½	8%	91%	93%	26%
	Bottom ½	2%	87%	52%	46%

* % of plated kernels with specified fungi.

the bottom half of the bin at the end of the thirteenth day, and the percentage of A. Flavus in the top half of the bin was 8% on the same day. The above percentages do not represent an alarming situation regarding A. Flavus. The percentage of Fusarium increased to an average of 89% for the entire bin, partly due to a high initial contamination of 46%. At the

end of the thirteenth day the bin showed a much higher contamination of Penicillium in the top half of the bin. Alternaria again increased especially in the bottom half of the bin. Overall, the corn was considered sound for feed when the experiment was terminated.

E. Experiment No. 4

Corn utilized for this experiment was from the same truckload as the grain used for experiment No. 3, but was stored for two weeks in a cooler kept at 40°F. A total of 450 lbs. (8 bushels) of corn were placed in both bins.

The experiment consisted of a natural ventilation test with a simulated wind speed of 5 mph (8 kmph) on the roof turbine, and a test employing no natural or forced ventilation through the other bin, and no corncobs in the chamber. The results of the unventilated case will give an indication of the advantages of the other system.

The unventilated bin was covered with its roof, but after the sixth day it was covered with a flat piece of plywood because the room's air decreased the moisture content of the corn in the top part of the bin. It is for this reason that a strict comparison between the two systems cannot be made. However, the effects of natural ventilation through corncobs were large enough as to provide positively conclusive results.

The simulated wind on the roof turbine created an airflow of about 5.25 cfm, which is equivalent to 0.65 cfm/bu. of corn. Since the bin contained 8 bushels, the air space between the top

grain surface and the roof was smaller than that of natural ventilation tests in experiments No. 1 and No. 2 which utilized only 6 bushels. Unless this airspace has an effect on the amount of air that the turbine is capable of pulling through the bin, it can be concluded that the lower airflow of natural ventilation tests in experiments No. 1 and No. 2 was due to air leakages through the eave of the bin, or to obstruction of the perforated floor from grain fines.

During the last part of this experiment a higher airflow was obtained through the outer zone of the ventilated bin, as deduced from the values of the moisture content in the outer and center zones of the bin. Corncobs for the ventilated bin were replaced approximatley every 48 hours.

Figure 23 shows the average moisture content in the bottom half of the ventialted and unventilated bins. It is important to recognize again that the top of the unventilated bin was not completely sealed, and the grain in the top and upper parts of the bin dried down to an average of 15.8% moisture content. The moisture content of the lower part is thus thought to be affected by the drier grain above, giving a lower average moisture content for the bottom part of the bin. However, it can be observed from Figure 23 that the final average moisture content of the ventilated bin was below 18% and decreasing, while that of the unventilated bin was 19.7% and increasing. The grain at the bottom layer of the ventilated bin dried to an average final moisture content of 17.1%, while that of the unventilated

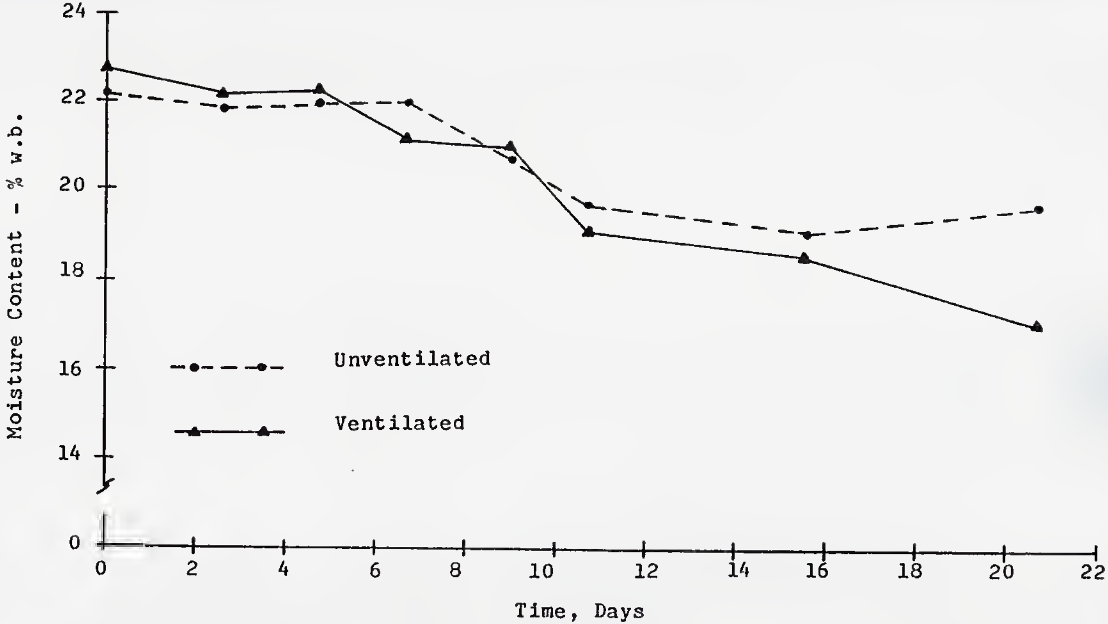


Figure 23. Average moisture content in the bottom half of the ventilated and unventialted bins during experiment No. 4.

bin had a moisture content of 20.2% when the experiment was terminated. The moisture contents at all four layers of both bins are given in Table A.16 and A.17 of the appendix. A total of 3.2 lbs. of corn were conditioned for each pound of corncobs used during the ventilated test.

Figure 24 shows the temperature at the midpoint of the bins for both tests of this experiment. Since the grain had been kept cold, the initial grain temperature was about 57°F. It can be observed how the temperature inside the ventilated bin increased to about 72°F after the first day and remained almost constant thereafter at about 75°F, showing no heating due to mold or bacteria growth. On the contrary, the temperature inside the unventilated bin progressively increased to about 114°F when the experiment was terminated.

Table 23 shows the average mold contamination for the bottom half of both bins. At the end of the experiment the unventilated bin had A. Flavus on 20% of the kernels, while none was detected in the ventilated bin.

The percentage of Penicillium was 55% in both bins when the experiment was terminated. The unventilated bin contained less Fusarium and Alternaria, both field fungi, perhaps indicating a more serious contamination of storage fungi. The high initial percentage of Alternaria might be explained by having stored the grain in cold temperatures.

Figures 23 and 24 and Table 23 show how much difference ventilating a bin can make on the quality of grain, even if it is

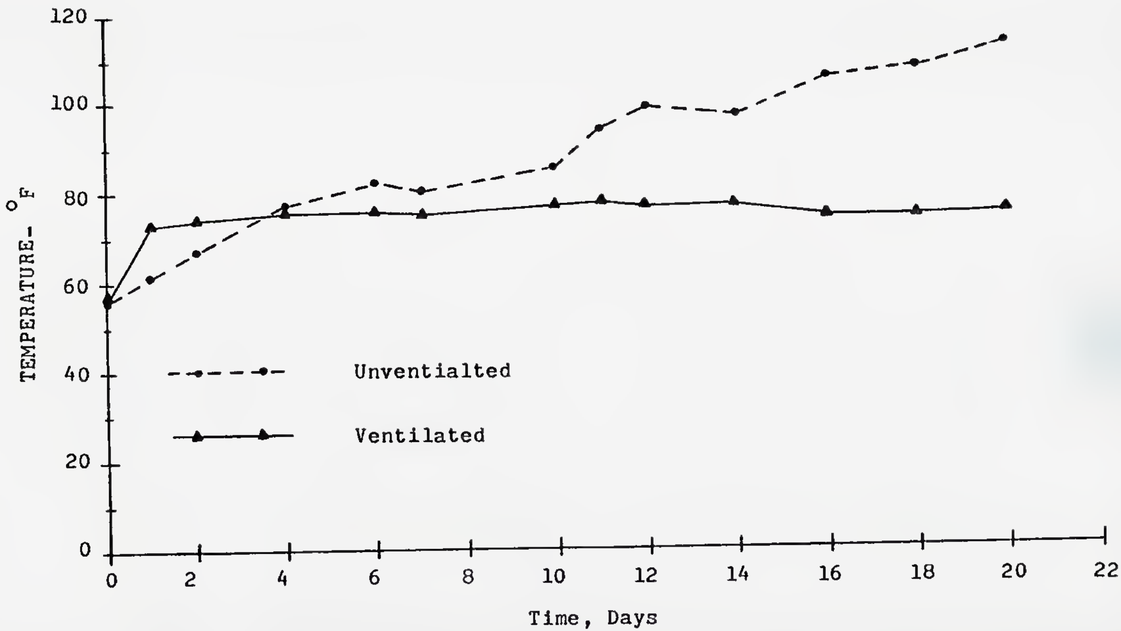


Figure 24. Temperature at the midpoint inside the ventilated and unventilated bins in experiment No. 4.

Table 23. Average mold contamination for the bottom half of the ventilated and unventilated bins in experiment No. 4.*

TIME	BIN	A. FLAVUS	FUSARIUM	PENICILLIUM	ALTERNARIA
Initial	Both	0%	68%	0%	44%
6 Days	Ventilated	2%	81%	39%	39%
	Unventilated	4%	80%	46%	30%
20 Days	Ventilated	0%	86%	55%	31%
	Unventilated	20%	76%	55%	18%

* % of plated kernels with specified fungi.

done with fairly high relative humidity. It is concluded, however, that natural ventilation through corncobs was not successful in drying the grain and entirely preserving its quality. If natural ventilation is to be used to condition grain by utilizing corncobs as a desiccant for high outside relative humidities, lower initial moisture content grain is desired, and both higher wind speeds and shallower grain depths are recommended.

F. Experiment No. 5

Corn used for this experiment was harvested in southern Nebraska at a moisture content of 19% w.b., and brought to

Manhattan by truck. The grain remained overnight in the tarpaulined trailer before it was cleaned with the Clipper M-2B cleaner. After cleaning, the corn was stored for two weeks in a cooler kept at 40°F. The grain was taken out of the cooler and stored in the shop for almost two days until its temperature reached about 68°F (20°C), before it was placed in the bins. A total of 450 lbs. (8 bushels) were placed in each bin.

The experiment consisted of two forced-air tests utilizing airflows of 1 and 2 cfm/bushel of corn. The experiment was allowed to run for a total of 33 days. The temperature of the grain increased after the first day of forced-air ventilation, and in both cases remained approximately constant. The average temperature of the lower and upper layers of the bin with 1 cfm/bu. was 78.5°F throughout the experiment, and 81.4°F for the bin with 2 cfm/bu. No sign of heating due to mold or bacteria growth was noticed in either case.

Corncobs were replaced approximately every 12 hours in the experiment with an airflow of 2 cfm/bu., and every 24 hours for the test employing 1 cfm/bu. The airflow across the bin utilizing 2 cfm/bu. was more or less uniform throughout the experiment. The moisture content in the center zone of the bin with 1 cfm/bu. showed to be somewhat lower than that of the outer zone during the last half of the experiment. Thus, it is concluded that there was more airflow going through the center of this bin during the last days of the experiment.

Figure 25 shows the average moisture content in the top

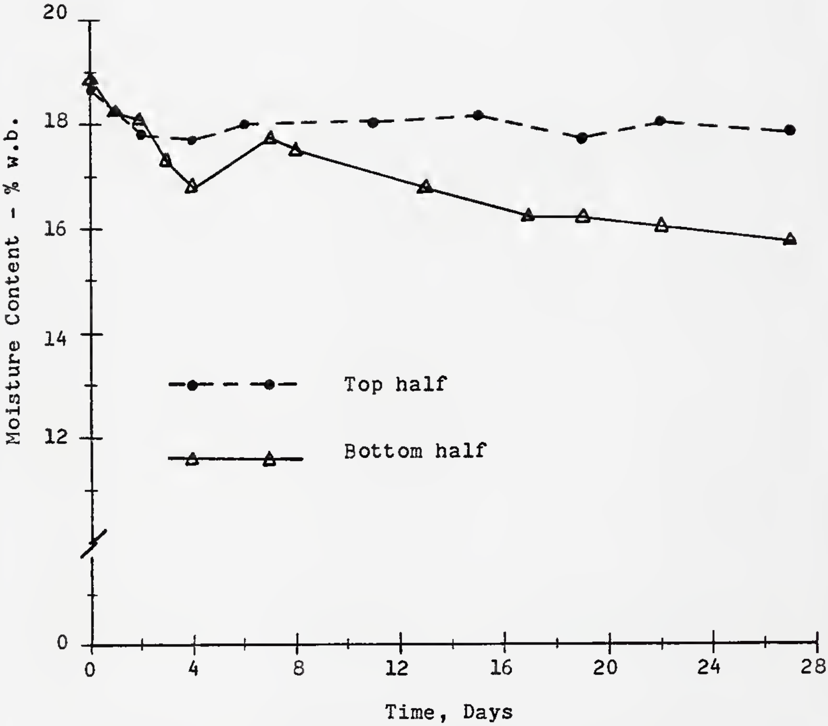


Figure 25. Average moisture content in the top and bottom halves of the bin with an airflow of 1 cfm/bu. during experiment No. 5.

and bottom halves of the bin with 1 cfm/bu. Moisture contents at all levels are given in Table A.18 of the appendix. It is unknown what occurred between the fourth and seventh day when the moisture content of the bottom layer increased again to 18%. In general, data from the first six days seem rather unreliable. The moisture content at the bottom layer was 15.3%, and 18.6% at the top layer when the experiment was terminated. Approximately one pound of corncobs was used to dry one pound of grain during this test.

Table 24 shows mold contamination data for the 1 cfm/bu. test. The percentage of fungi shown was more or less uniform in all layers, thus data was averaged for the entire bin. It can be observed that practically no A. Flavus was detected. About twice as much A. Glaucus was detected at the end of the experiment than at the beginning, but no other large percentage increases occurred. Overall, the grain was considered sound for feed.

Figure 26 shows the average moisture content in the top and bottom halves of the bin with an airflow of 2 cfm/bu. during this experiment. Moisture contents at individual layers are given in Table A.19 of the appendix. The moisture content at the bottom layer was 13.8% w.b., and 15.2% at the top layer when the experiment was terminated.

Table 25 shows the percentage of kernels contaminated with different kinds of fungi during this test. Data shown are averages for the entire bin. Results are very similar to those

Table 24. Average mold contamination data for entire bin with 1 cfm/bu. during experiment no. 5.*

TIME	A. FLAVUS	A. GLAUCUS	PENICILLIUM	FUSARIUM
Initial	0%	28%	6%	67%
8 Days	0.5%	47%	8%	53%
25 Days	0%	59%	15%	43%
33 Days	0%	57%	17%	56%

* % of plated kernels with specified fungi.

Table 25. Average percentage of kernels contaminated with different kinds of fungi during the test utilizing 2 cfm/bu. in experiment No. 5.

TIME	A. FLAVUS	A.GLAUCUS	PENICILLIUM	FUSARIUM
Initial	0%	28%	6%	67%
8 Days	0.5%	49%	8%	48%
25 Days	0%	51%	20%	51%
33 Days	0%	54%	16%	59%

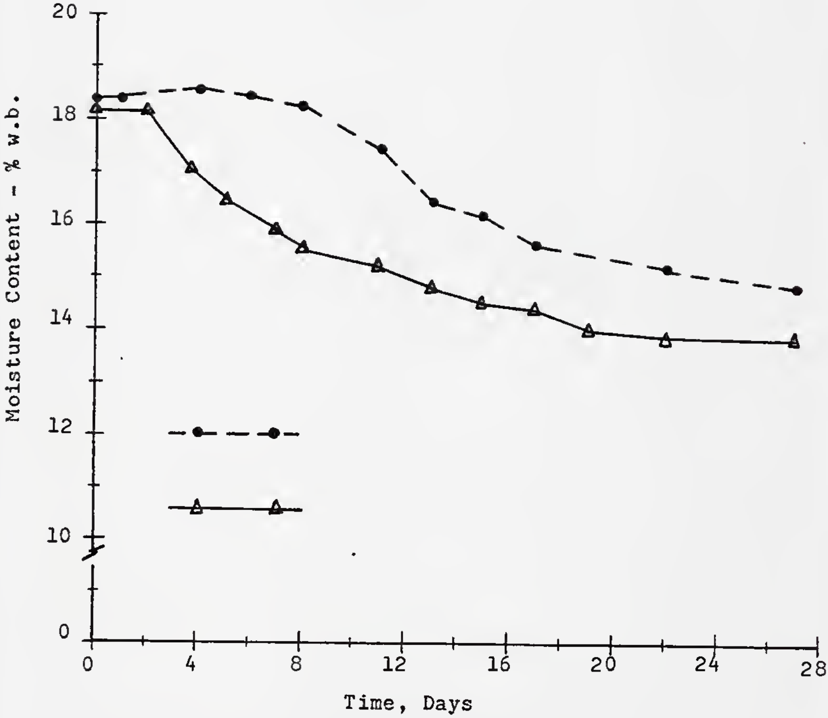


Figure 26. Average moisture content in the top and bottom halves of the bin with an airflow of 2 cfm/bu. during experiment No. 5.

of the 1 cfm/bu. test. Grain from both bins was considered sound for feed.

It is concluded that for an initial moisture content of 18.5%, an airflow of 2 cfm/bu. and other conditions of this test, grain can be dried to 14% M.C. without appreciable deterioration. However, after the thirty-three days that this test lasted, approximately two pounds of corncobs were used for each pound of corn dried.

G. Discussion

Results showed that the quantity of corncobs used in each chamber can provide an average relative humidity decrease of 12 to 23% from that inside the environmental chamber, during the adsorption period. The average decrease in relative humidity depends on the initial moisture content of the corncobs and the airflow utilized.

It is conceivable then that air with an approximate relative humidity of 60 to 70% can be obtained from an environment with an average relative humidity of 83%, by utilizing corncobs as a desiccant. Grain could thus be dried to 13.5 or 14% moisture content, which would be otherwise impossible.

A decrease in the average relative humidity can be obtained by reducing the airflow or by shortening the corncobs adsorption cycle. However, low airflows and short adsorption cycles are not considered practical.

Drying high moisture grain with air at average relative

humidities of 60 to 70% can take very long, and result in quality deterioration. Furthermore, large quantities of corncobs are required as the number of regeneration times increases. Results from the forced-air tests indicated that the total amount of corncobs used can be equal to or grater than the amount of corn dried. Assuming that the corncobs from each batch used are initially at 2% moisture content and are replaced at 10% moisture content, as much as 35 to 70 pounds of water would have to be removed from the corncobs in order to dry 450 lbs. of 23% moisture corn to 14% w.b. The amount of energy required to remove the water from the corncobs would then be approximately equal to or greater than the energy otherwise required to remove the desired amount of water from the grain.

Unless large quantities of dry corncobs are available before the grain drying operation, utilizing corncobs as a desiccant to perform most of the drying is not recommended.

However, corncobs can be useful in holding grain for a few days to prevent quality deterioration before drying, or to provide partial drying. Corncobs could also be used as a desiccant to level off high humidity peaks during natural grain drying.

Corn to corncob weight ratios of about 30:1 are considered appropriate to provide partial drying or grain conditioning. In any case, grain depths should be moderate. Corncobs should be replaced when they attain 70 to 80% of their total adsorptive capacity. The following are the airflows recommended to

condition grain at different moisture contents:

Grain Moisture Content (% w.b.)	Airflow (cfm/lb. of cobs)
$\geqslant$ 25%	2.7
21-24%	1.6
17-20%	1.0
14-16%	0.5

Using natural ventilation through corncobs as a desiccant to condition high moisture grain is not recommended. If natural ventilation is to ever be used, the initial moisture content of the grain should be less than 18%, and windspeeds should be greater than 7.5 mph (12 kmph).

CONCLUSIONS

The following conclusions are drawn from the study:

Part I

1. Adsorption isotherms for corncobs are of the sigmoid type, as those for most cereal grains.
2. There is no difference in the equilibrium moisture content of ground, whole, and chopped corncobs as defined in this study.
3. The equilibrium moisture content of corncobs decreases with an increase in temperature, due to the lesser dependence on temperature of the sorption forces than that of water vapor pressure.
4. The Chung and Pfost equation describes very well the adsorption isotherms for corncobs in two ranges.
5. The heat of adsorption of corncobs at 81°F from 2 to 25% moisture content ranges from 1512 to 1084 Btu/lb.H_2O respectively. The heat of adsorption of corncobs increases rapidly at low moisture contents.
6. The rate of water vapor adsorption for static conditions depends on the structure of the corncobs, their initial moisture content, and the environmental conditions.
7. Ground corncobs show a higher rate of water vapor adsorption than whole and chopped cobs.
8. The simplified model developed describes well the rate of

water vapor adsorption by corncobs, especially during the first 48 hours of adsorption.

9. Moderate drying temperatures do not affect the adsorptive capacity of corncobs.
10. Successive wetting and drying cycles do not affect the adsorptive capacity of corncobs.

Part II

1. The heat of adsorption of dry corncobs can substantially increase the temperature of flowing air, especially during the first minutes of adsorption.
2. An average relative humidity decrease of 12 to 23% was obtained over a 12 hour period by passing 83% relative humidity air through 15 pounds of corncobs at rates ranging from 0.5 to 1.5 cfm per pound of cobs.
3. The regeneration period for the corncobs depends on their initial moisture content, the airflow rate, the amount of cobs used, and the environmental conditions of the flowing air. For the conditions of this study, the regeneration period varied from 12 to 48 hours.
4. Grain drying and conditioning in humid climates can be accomplished utilizing the proposed system, provided that sufficiently dry corncobs are replaced when 70 to 80% of their adsorptive capacity is used up, and that adequate airflow is supplied.
5. For the conditions of this study, the lowest moisture content that the grain attained was 13.5 to 14% w.b.

6. Total corncob to corn weight ratios from 1 to 2.5 may be needed to dry grain from 22 to 14% moisture content. The large amount of energy required to dry the corncobs (or regenerate them) does not justify their use to dry grain from moisture contents around 22% down to 14%.
7. Corncobs can be used to provide partial drying or conditioning, or to hold grain before drying.
8. Corncobs can be used to level off high humidity peaks when natural grain drying is required.
9. The natural ventilation system studied is not recommended, unless grain at a moisture content of 17% or less is being conditioned and wind speeds of 8 mph. are available at all times.
10. Conditioning should begin as soon as possible after harvesting the grain.

SUGGESTIONS FOR FURTHER RESEARCH

The following suggestions are recommended for further research:

1. Develop a model to predict the rate of water vapor adsorption by corncobs under dynamic conditions. Perhaps a modification of the model proposed for static conditions could provide satisfactory results.
2. Study an effective and efficient way to regenerate the corncobs.
3. Test the forced-air system in actual humid environments to provide grain conditioning.
4. Study a method of applying corncobs as a desiccant to level off high humidity peaks in all regions where natural grain drying is utilized.
5. Investigate the utilization of corncobs as a commercial desiccant.

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REFERENCES

Agricultural Engineers Yearbook. 1976. Published by the American Society of Agricultural Engineers. St. Joseph, Michigan.

Arnold, L. K. 1975. The commercial utilization of corncobs. In solid wastes, origin, collection, processing and disposal. C.L. Mantell. Editor. P. 393-401. John Wiley and Sons, New York.

ASHRAE Handbook of Fundamentals. 1977. Published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. New York.

Ayerst, G. 1965. Water Activity. Its measurement and significance in biology. Int. Biodeterior Bull. 1: 13-26.

Babbitt, J.D. 1949. Observations on the adsorption of water vapor by wheat. Can. J. Res. 27F: 55-72.

Bailey, J.E. 1974. Whole grain storage. In Storage of cereal grains and their products. C.M. Christensen. Editor. P. 333-360. Am. Soc. Cereal Chemists. St. Paul, Minnesota.

Becker, H.A., and H.P. Sallans. 1956. A study of the desorption isotherms of wheat at 25°C and 50°C. Cereal Chem. 33: 79-91.

Bergter, F. 1912. Ann der Phys., (5), 37, 472.

Brooker, D.B., F. Bakker-Arkema, and C. Hall. 1974. Drying cereal grains. The AVI Publishing Company, Westport, Connecticut.

Brunauer, S., P.H. Emmet, and E. Teller. 1938. Adsorption of gases in multimolecular layers. J. Am. Chem. Soc. 60: 309-319.

Brunauer, S. 1943. The adsorption of gases and vapors. Physical adsorption. Princeton: Princeton Univ. Press.

Bushuk, W. and C.A. Winkler. 1957. Sorption of water vapor on wheat flour, starch, and gluten. Cereal Chem. 34: 73-86.

Chemical Engineers' Handbook. 1950. Third Edition. McGraw-Hill Book Company, Inc., New York.

Christensen, C. M. 1974. Storage of cereal grains and their products. Published by the American Society of Cereal Chemists. St. Paul, Minnesota.

Chung, D.S. and H.B. Pfost. 1967. Adsorption and desorption of water vapor by cereal grains and their products. Parts I, II, III. Trans. ASAE 10(4): 549-557.

Damköhler, G. 1935. Z. Phys. Chem., A174, 222.

Danziger, M.T., et al. 1972. Drying of field corn with silica gel. Trans. ASAE 15(6): 1071-1074.

DeBoer, J.H. 1953. Dynamical character of adsorption. The Clarendon Press, Oxford, England.

Dunstan, E. 1972. Adsorption-desorption characteristics of grain sorghum. Unpublished M. S. thesis. Kansas State University. Manhattan, Kansas.

Dunstan, E.R., D.S. Chung, and T.O. Hodges. 1974. Adsorption and desorption characteristics of grain sorghum. Trans. ASAE 16(4): 667-670.

Fleske, L.F. 1973. Application of drying agents for small scale on-farm drying and storage in humid regions of developing countries. Unpublished M. S. thesis. Kansas State University. Manhattan, Kansas.

Florida Cooperative Extension Service. 1977. Use of moldy feeds for livestock and poultry. A composite information. Inst. of Food and Ag. Sci., University of Florida.

Gregg, S.J., and K.S. Sing. 1967. Adsorption, surface area and porosity. Academic Press, London and New York.

Hall, D.W. 1970. Handling and storage of food grains in tropical and subtropical areas. FAO Paper No. 90.

Henderson, S.M. 1952. A basic concept of equilibrium moisture. Ag. Eng. 33: 29-32.

Henderson, S.M., and R.L. Perry. 1966. Agricultural process engineering. Second edition. Library of Congress: 54-126.84.

Hougen and Marshal. 1947. Chem. Eng. Progress, 43(4), 197.

Hsiao, J. 1974. Application of silica gel for on-farm grain drying and storage in developing countries. Unpublished M. S. thesis. Kansas State University. Manhattan, Kansas.

Hukill, W.V. 1947. Basic principles in drying corn and grain sorghum. Agr. Eng. 28: 335-338.

Hukill, W.V. 1974. Grain Drying. In Storage of cereal grains and their products. C.M. Christensen. Editor. P. 481-508. Am. Soc. Cereal Chemists. St. Paul, Minnesota.

Hunt, W.H. and S.W. Pixton. 1974. Moisture - Its significance, behavior, and measurement. In Storage of cereal grains and their grpducts. P. 1-52.

Hyde, M.B. 1974. Airtight storage. In Storage of cereal grain and their products. P. 303-419.

Hygrodynamics. Technical Bulletin No. 5. Creating and Maintaining humidities by salt solutions. Hygrodynamics Inc., Silverspring, Maryland.

Jones, C.R. 1951. Evaporation in low vacuum from warm granular materials (wheat) during the falling rate period. J. Sci. Fd. Agric. 2: 565.

Labuza, T.P. 1968. Sorption Phenomena in Foods. Food Technol. 22: 263-272.

Langmuir, I. 1918. J. Am. Chem. Soc., 40, 1361.

Ledoux, E. 1945. Vapor adsorption. Chemical Publishing Co., Brooklyn, New York.

Miller, E.B. 1920. Adsorption by silica gel I. Chemical and Metallurgical Engineering. 23(24): 1155-1520.

McBain, J.W. 1909. Z. Phys. Chem., 68, 471.

McEwen, E., W.H. Simmonds, and G.T. Ward. 1954. Drying of Wheat grain. Part III. Interpretation in terms of biological structure. Trans. Inst. Chem. Eng. 32: 115-120.

Muckle, T.R. and H.G. Stirling. 1971. Review of the drying of cereals and legumes in the tropics. Tropical Stored Products Information. No. 22.

Park, S.W., D.S. Chung, and C.A. Watson. 1971 and 1972. Adsorption kinetics of water vapor by yellow corn. Parts I and II. Cereal Chemistry. Vol. 48, (14), and Vol. 49, (598).

Peterson, Anne, V. Schlegel, B. Hummel, L.S. Cuendent, W.F. Geddes, and C.M. Christensen. 1956. Grain storage studies. XXII. Influence of oxygen and carbon dioxide concentrations

on mold growth and grain deterioration. Cereal Chemistry. 33: 53-66.

Pierce, C., and R.N. Smith. 1950. Adsorption desorption hysteresis in relation to capillarity of adsorbents. J. Phys. Colloid Chem. 54: 784-794.

Pfost, H.B. et al. 1976. Summarizing and reporting equilibrium moisture data for grains. Presented at the 1976 Winter meeting of the ASAE. Paper No. 76-3520. Palmer House, Chicago.

Ponec, V., A. Knör, and S. Černý. 1974. Adsorption on solids. Buttersworth Group. Prague, Czechoslovakia.

Rodriguez-Arias, J.H., C.W. Hall and F.W. Bakker-Arkema. 1963. Heat of vaporization for shelled corn. Cereal Chem. 40: 676-683.

Ross, S. and J.P. Oliver. 1964. On physical adsorption. John Wiley and Sons, Inc. New York.

Smith, S.E. 1947. The sorption of water vapor by high polymers. J. Am. Chem. Soc. 69: 646-651.

Solomon, M.E. 1951. Control of humidity with potassium hydroxide, sulfuric acid, or other solutions. Bulletin of Entomological Res. Vol. 42 P. 543.

Theimer, O. 1951. Hutigs adsorption isotherm. Nature (London) 168: 873.

Thompson, T.F. 1972. Temporary storage of high-moisture shelled corn using continuous aeration. Trans. ASAE, Vol. 15.

Threlkeld, J.L. 1962. Thermal Environmental Engineering. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Tuite, J. and G.H. Foster. 1963. Effect of artificial drying on the hygroscopic properties of corn. Journal Paper No. 2083, Purdue University. Ag. Exp. Station. West Lafayette, Indiana.

Young, J.H. and G.L. Nelson. 1967. Theory of hysteresis between sorption and desorption isotherms in biological materials. Trans. ASAE 10(2): 260.

APPENDIX

Table A. 1. Adsorption data for ground, whole, and chopped corncobs at 72°F and 86% relative humidity.*

TIME (Hrs)	MOISTURE CONTENT - % d.b.		
	GROUND	WHOLE	CHOPPED
Initial	3.62	3.51	3.33
12	12.84	9.84	12.24
24	15.44	12.51	15.04
48.5	17.44	16.16	17.65
72	17.96	17.38	18.64
101.5	18.46	18.34	19.47
122.5	18.86	18.91	19.92
144	19.05	19.26	20.20
168	18.96	19.25	20.16
198	19.00	19.25	20.14

* Cobs predried at 95°F.

Table A. 2. Adsorption data for ground, whole, and chopped corncobs at 72°F and 86% relative humidity.*

TIME (Hrs)	MOISTURE CONTENT - % d.b. GROUND	WHOLE	CHOPPED
Initial	1.17	1.24	1.41
12	13.19	9.16	10.79
24	16.33	13.14	14.92
48.5	17.95	16.18	18.06
72	18.32	17.57	18.85
101.5	18.73	18.53	19.52
122.5	19.09	19.10	20.17
144	19.24	19.41	20.33
168	19.12	19.41	20.26
198	19.16	19.32	20.15

* Cobs predried at 140°F.

Table A. 3. Adsorption data for ground, whole, and chopped corncobs at 72°F and 86% relative humidity.*

TIME (Hrs)	MOISTURE CONTENT - % d.b. GROUND	WHOLE	CHOPPED
Initial	0.424	0.555	0.498
10	10.11	9.38	8.67
24	14.97	13.88	13.24
48	17.91	17.21	16.95
72	18.84	18.53	18.47
96	19.18	19.01	19.44
120	19.39	19.22	19.91
150	19.42	19.29	20.07
168	19.49	19.36	20.22
192	19.25	19.29	20.16
216.5	19.41	19.36	20.14
246	19.39	19.36	20.24

* Cobs predried at 180°F.

Table A. 4. Adsorption data for ground, whole, and chopped corncobs at 72°F and 61% relative humidity. Replication 1.

TIME (Hrs)	MOISTURE CONTENT - % d.b. GROUND	WHOLE	CHOPPED
Initial	2.26	2.54	2.39
9½	8.14	7.26	6.79
29½	10.43	9.86	9.34
53-3/4	10.79	10.70	10.21
78½	10.78	10.83	10.40
102	10.81	10.90	10.50
126-3/4	10.82	10.92	10.58
150-3/4	10.81	10.91	10.61
172-¼	10.81	10.91	10.61

Table A. 5. Adsorption data for ground, whole, and chopped corncobs at 72°F and 61% relative humidity. Replication 2.

TIME (Hrs)	MOISTURE CONTENT - % d.b. GROUND	WHOLE	CHOPPED
Initial	5.13	6.20	5.65
11½	9.30	8.93	8.65
33-3/4	10.31	10.16	10.10
58½	10.46	10.54	10.41
82¼	10.51	10.67	10.53
101½	10.51	10.71	10.67
120	10.51	10.73	10.68
149½	10.59	10.79	10.71
167½	10.61	10.83	10.78

Table A. 6. Adsorption data for ground, whole, and chopped corncobs at 80°F and 61% relative humidity.

TIME (Hrs)	MOISTURE CONTENT - % d.b.		
	GROUND	WHOLE	CHOPPED
Initial	5.56	6.62	6.32
16½	10.29	10.20	10.11
23½	10.43	10.45	10.33
47½	10.53	10.76	10.79
72	10.60	10.86	10.94
96	10.63	10.89	10.94
126	10.64	10.89	10.96
149	10.57	10.81	10.90
162	10.57	10.80	10.90

Table A. 7. Adsorption data for ground, whole, and chopped corncobs at 80°F and 85% relative humidity.

TIME (Hrs)	MOISTURE CONTENT - % d.b. GROUND	WHOLE	CHOPPED
Initial	5.43	6.33	6.20
6	13.04	12.11	11.11
25.5	17.66	16.59	15.66
47	18.36	17.78	17.51
73	18.63	18.30	18.17
98	18.97	18.75	18.88
127	18.89	18.79	18.98
145	18.77	18.72	18.91
168	18.65	18.62	18.84

Table A. 8. Adsorption data for ground, whole, and chopped corncobs at 90°F and 60% relative humidity. Replication 1.

TIME (Hrs)	MOISTURE CONTENT - % d.b. GROUND	WHOLE	CHOPPED
Initial	9.12	8.76	8.91
6	9.39	9.27	9.42
24.5	9.59	9.67	9.89
48	9.61	9.75	9.97
72	9.61	9.77	9.97
92.5	9.58	9.76	9.97

Table A. 9. Adsorption data for ground, whole and chopped corncobs at 90°F and 60% relative humidity. Replication 2.

TIME	MOISTURE CONTENT - % d.b.		
(Hrs)	GROUND	WHOLE	CHOPPED
Initial	5.46	6.01	6.32
5	8.42	8.12	8.47
25	9.11	9.18	9.46
54	9.18	9.35	9.63
75	9.23	9.42	9.70
99	9.31	9.49	9.78
123	9.23	9.44	9.73
146	9.28	9.49	9.74

Table A. 10. Adsorption data for ground, whole, and chopped corncobs at 90°F and 83% relative humidity.

TIME (Hrs)	MOISTURE CONTENT - % d.b. GROUND	WHOLE	CHOPPED
Initial	5.04	4.95	5.17
7	13.67	12.03	11.80
24	15.81	15.14	15.16
48	16.30	16.16	16.40
74	16.58	16.51	16.91
106	16.68	16.70	17.17
126	16.63	16.64	17.11

Table A.11. Average moisture content at the top, center, and bottom layers of the corn bin utilized for the natural ventilation test in experiment No. 1.

TIME (Hours)	MOISTURE CONTENT - % w.b. TOP	CENTER	BOTTOM
0	23.7	24.3	24.2
16	24.0	24.2	24.0
41	23.1	23.8	23.6
73	24.0	23.0	23.8
97	23.9	21.3	22.4
144	24.9	22.8	20.7

Table A.12. Average moisture content at four layers of the corn bin with an airlfow of 3 cfm/bu. during experiment No. 2.

TIME (Hours)	MOISTURE CONTENT - % w.b. TOP	CENTER	BOTTOM
0	23.7	24.3	24.2
16	24.0	24.2	24.0
41	23.1	23.8	23.6
73	24.0	23.0	23.8
97	23.9	21.3	22.4
144	24.9	22.8	20.7

Table A.13. Average moisture content at the top, center, and bottom layers of the corn bin utilized for the natural ventilation test in experiment No. 2.

TIME (Hours)	MOISTURE CONTENT - % d.b. TOP	CENTER	BOTTOM
0	15.5	15.7	15.7
24	15.4	15.9	15.9
48	15.3	15.8	15.8
76	14.9	15.7	16.0
113	15.0	15.8	15.8
140	14.3	15.0	15.5
160	13.3	14.9	14.6

Table A.14. Average moisture content at four layers of the corn bin with an airflow of 2 cfm/bu. during experiment No. 3.

TIME (Days)	Hours	MOISTURE CONTENT - % w.b. TOP	UPPER	LOWER	BOTTOM
Initial	0	22.9	23.4	23.2	23.4
(1.2)	29	23.4	23.3	23.2	23.2
(2.2)	53	23.7	23.3	23.2	23.2
(3.0)	71	23.5	23.1	22.9	22.0
(3.9)	94	23.4	23.1	22.9	21.9
(5.8)	138	23.2	22.6	22.4	18.1
(6.9)	165	23.1	22.0	20.6	15.5
(9.0)	215	22.4	22.0	20.8	14.8
(9.9)	238	21.9	21.9	20.5	14.6
(11.8)	284	21.0	20.7	17.5	13.6
(13.1)	316	21.2	20.7	16.4	13.5

Table A.15. Average moisture content at four layers of the corn bin with an airflow of 3 cfm/bu. during experiment No. 3.

TIME (Days) - Hours		MOISTURE CONTENT - % w.b. TOP	UPPER	LOWER	BOTTOM
Initial	0	23.0	22.9	23.4	23.2
(1.2)	29	23.4	23.2	23.3	22.8
(2.2)	53	23.7	23.2	23.2	21.3
(3.0)	71	23.3	23.0	22.9	19.5
(3.9)	94	23.1	23.0	22.9	17.9
(5.8)	138	22.9	22.5	20.3	14.9
(6.9)	165	22.6	22.0	17.6	14.1
(9.0)	215	22.2	19.6	15.3	14.3
(9.9)	238	21.6	18.4	15.1	14.2
(11.8)	284	20.2	16.6	14.2	13.8
(13.1)	316	19.5	15.4	14.0	13.7

Table A.16. Average moisture content at four layers of the unventilated corn bin during experiment No. 4.

TIME (Days)	MOISTURE CONTENT - % w.b.			
	TOP	UPPER	LOWER	BOTTOM
0	21.9	21.6	22.3	21.9
2.60	18.7	21.7	21.8	21.8
4.75	12.5	18.7	21.9	22.1
6.70	14.4	20.9	21.9	22.2
9.0	13.7	18.1	20.1	21.5
10.7	-----	14.6	18.8	20.5
15.5	12.9	14.4	17.7	20.5
20.7	13.9	17.7	19.1	20.2

Table A.17. Average moisture content at four layers of the ventilated bin during experiment No. 4.

TIME (Days)	MOISTURE CONTENT - % w.b. TOP	UPPER	LOWER	BOTTOM
0	22.8	22.4	23.2	22.4
2.6	21.5	22.8	22.5	22.3
4.75	21.7	22.5	22.8	22.3
6.70	21.2	21.3	21.6	21.1
9.0	20.4	21.3	21.4	20.6
10.7	21.5	20.7	20.5	18.0
15.5	20.2	19.6	19.6	17.6
20.7	18.8	18.6	18.3	17.1

Table A.18. Average moisture content at four layers of the corn bin with an airflow of 1 cfm/bu. during experiment No. 5.

TIME	MOISTURE CONTNET - % w.b.			
(Days)	TOP	UPPER	LOWER	BOTTOM
0	18.8	18.6	18.5	19.2
1	18.0	----	18.1	18.2
2	18.1	17.4	17.8	18.2
3	17.8	----	17.6	16.9
4	17.8	17.6	17.4	16.2
5	17.4	17.6	17.7	16.1
6	18.3	17.7	18.1	18.0
7	18.1	17.7	17.9	17.7
8	18.2	----	17.6	17.3
11	18.2	17.8	----	16.0
13	18.3	17.8	17.6	16.0
15	18.6	17.7	17.7	16.0
17	18.9	17.8	17.3	15.5
19	18.7	17.6	17.0	15.8
22	18.8	17.5	16.6	15.4
27	18.6	17.2	16.3	15.3

Table A.19. Average moisture content at four layers of the corn bin with 2 cfm/bu. during experiment No. 5.

TIME (Days)	MOISTURE CONTENT - % w.b. TOP	UPPER	LOWER	BOTTOM
0	18.6	18.2	17.2	18.4
1	18.4	18.4	----	18.2
2	18.3	19.0	18.5	18.2
3	18.0	18.9	17.9	16.3
4	18.7	18.4	18.3	15.6
5	18.7	18.6	17.6	15.4
6	18.6	18.3	17.5	15.2
7	18.5	18.0	16.8	14.9
8	18.6	18.0	16.3	14.6
11	18.4	16.6	15.3	----
13	17.3	15.5	14.9	14.6
15	17.0	15.3	14.6	14.6
17	16.2	14.9	14.5	14.2
19	----	14.7	14.2	13.7
22	15.7	14.6	14.1	13.7
27	15.2	14.4	14.0	13.8

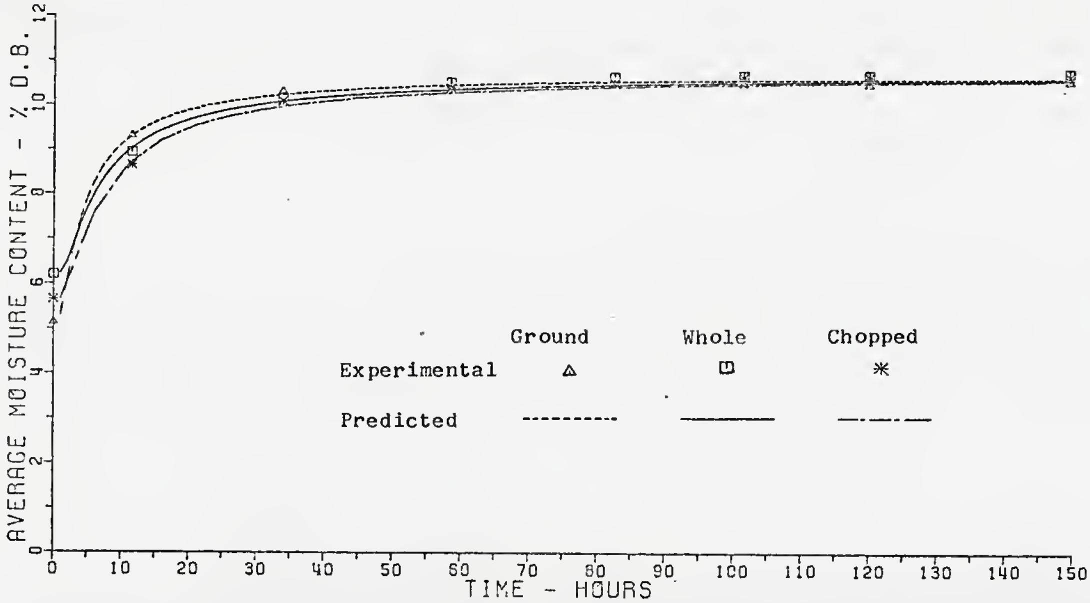

Figure A.1. Experimental and predicted values of the moisture content of ground, whole, and chopped corncobs during adsorption at 72°F and 61% relative humidity.

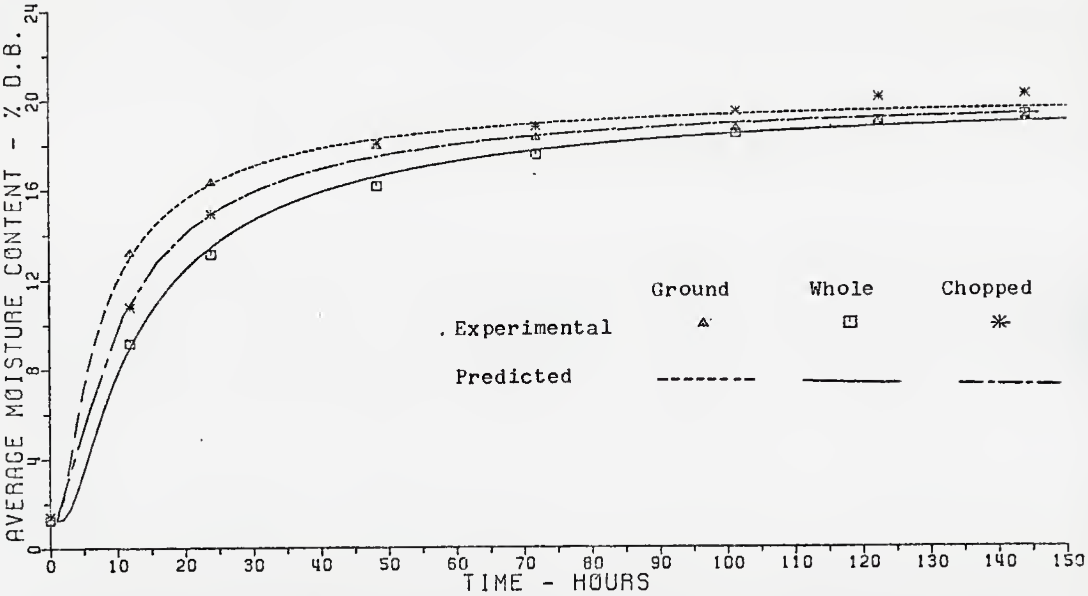

Figure A.2. Experimental and predicted values of the moisture content of ground, whole, and chopped corncobs during adsorption at 72°F and 86% relative humidity.

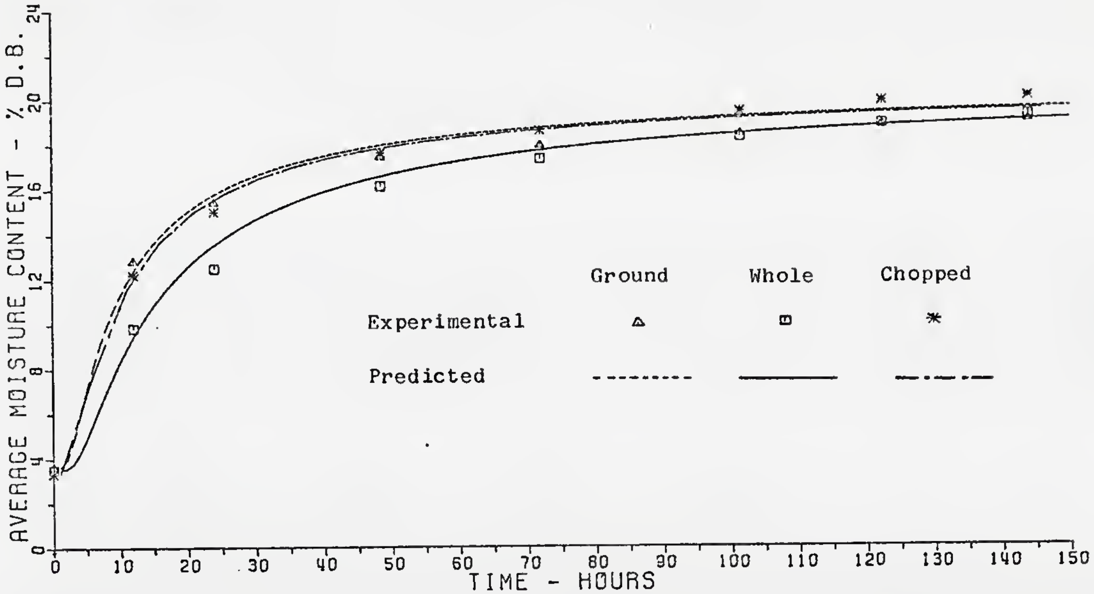

Figure A.3. Experimental and predicted values of the moisture content of ground, whole, and chopped corncobs during adsorption at 72°F and 86% relative humidity.

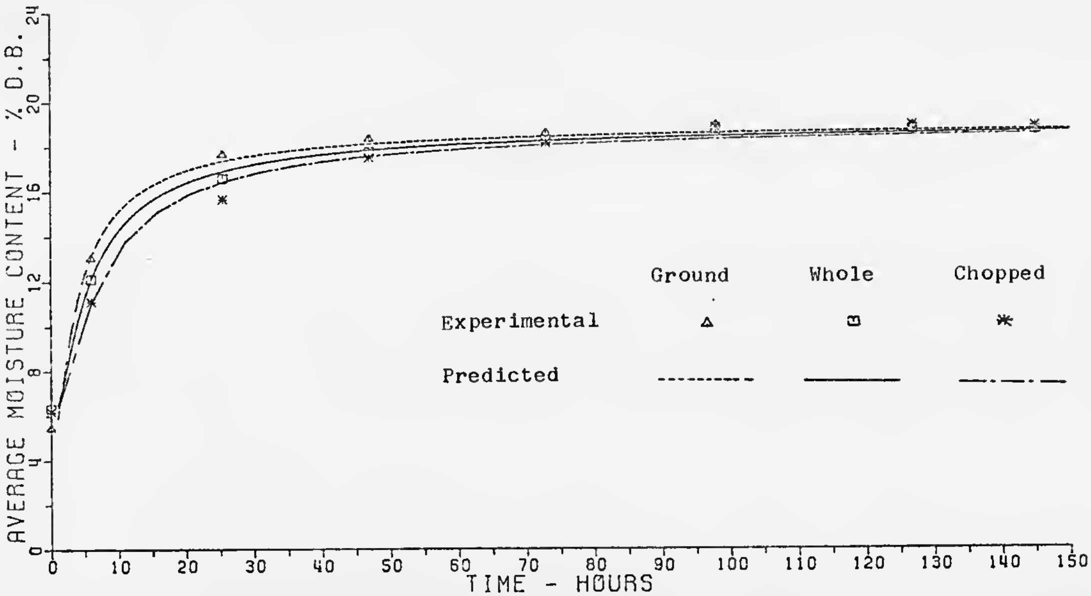

Figure A.4. Experimental and predicted values of the moisture content of ground, whole, and chopped corncobs during adsorption at 80°F and 85% relative humidity.

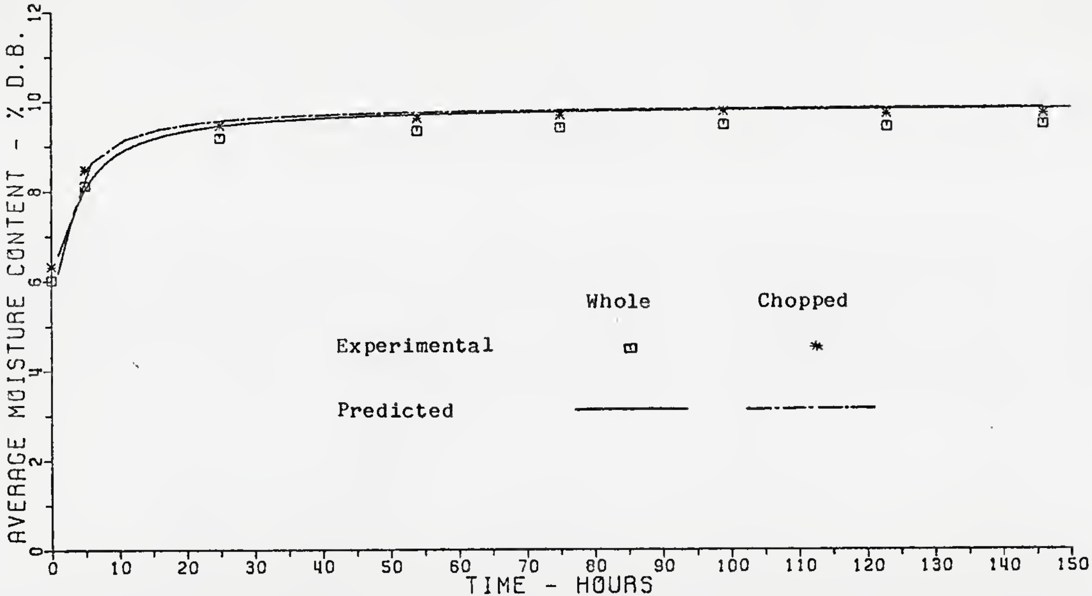

Figure A.5. Experimental and predicted values of the moisture content of whole and chopped corncobs during adsorption at 90°F and 60% relative humidity.

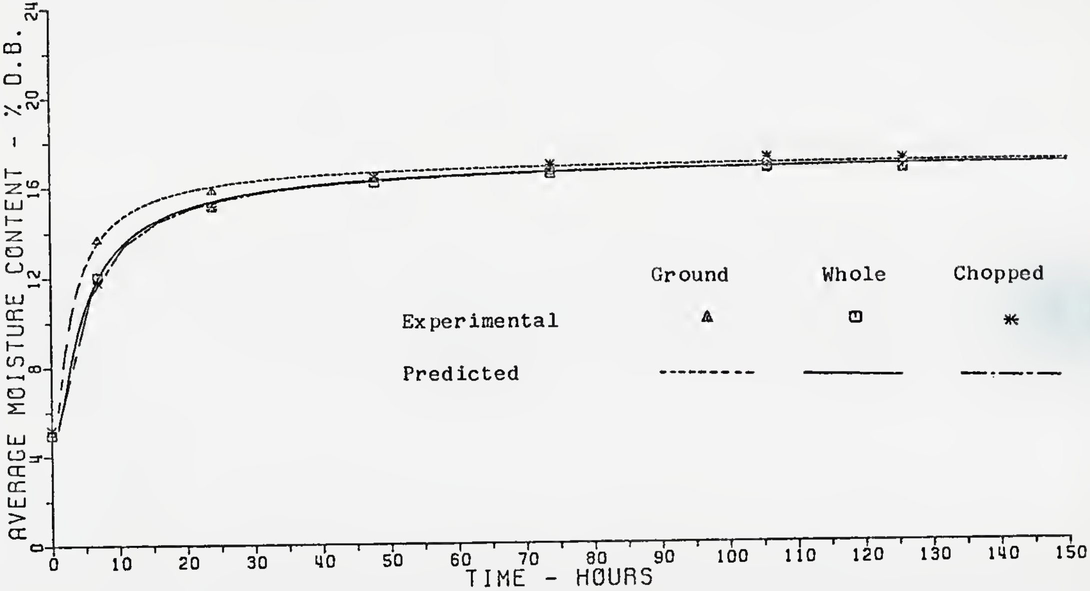

Figure A.6. Experimental and predicted values of the moisture content of ground, whole, and chopped corncobs during adsorption at 90 F and 83% relative humidity.

HYGROSCOPIC PROPERTIES OF CORNCOBS AND THEIR APPLICATION FOR SMALL SCALE ON-FARM GRAIN CONDITIONING

by

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The main objectives for this study were to obtain hygroscopic properties of corncobs, and investigate their application as a desiccant to dehumidify air in tropical climates for small scale grain drying and conditioning.

Work on the hygroscopic properties consisted of obtaining the relationship between equilibrium moisture content and relative humidity (Isotherms), and the rates of water vapor adsorption during static conditions by ground, chopped, and whole corncobs. Data for the rates of water vapor adsorption were collected at three temperatures (72°F, 80°F, and 90°F) and two relative humidities for each temperature level (86% and 61%). Data for isotherms were collected at the same temperatures and eight different relative humidity levels ranging from 10% to 92% for each temperature.

The Chung and Pfost equation for isotherms was shown to describe the equilibrium moisture content of corncobs at different relative humidities in two ranges. Constants in the equation were evaluated for each range at the three temperatures, as well as a combined equation for temperatures ranging from 70°F to 90°F.

A model was developed to describe the moisture content of the corncobs at anytime during static adsorption, given their initial moisture content and the environmental conditions in which they are placed. The model is of the form:

$$\frac{\bar{M}_t - M_o}{M_e - M_o} = \exp(-k/t)$$

where $\bar{M}_t$ is the average moisture content at any time t, M_o is the initial moisture content of the corncobs, M_e is the equilibrium moisture content found from the Chung and Pfost equation, and k is a constant. The constant k seems to depend on the partial vapor pressure inside the corncobs at the initial moisture content at the given environmental conditions.

It was found that drying the corncobs with moderate temperatures does not affect their final adsorptive capacity. Successive wetting and drying cycles of the corncobs do not seem to affect their adsorptive capacity.

To investigate the performance of the corncobs in a grain conditioning system, the cobs were placed in chambers adjacent to corn bins and humid air was drawn from an environmental chamber kept at 83% relative humidity. A corn to corncob weight ratio of about 30 was utilized in most cases.

Corn at initial moisture contents of 25%, 23%, 19% and 16% was employed. Airflows of 3, 2, and 1 cfm per bushel of corn were experimented, as well as a natural ventilation system utilizing a roof spinner on top of the grain bin.

Corncobs were replaced when the relative humidity on the outlet side of the corncob chamber reached 72 to 78%. Regeneration time varied from 12 hours for the higher airflows to 24 and 48 hours for low airflows and natural ventilation.

Grain drying and conditioning in humid climates can be accomplished utilizing the proposed system, provided that sufficiently dry corncobs are replaced when 70 to 80% of their adsorptive capacity is used up, and that adequate airflow is supplied.

However, the large amount of energy required to dry the corncobs (or regenerate them) does not justify their use to dry grain from 22% moisture content down to 14%.

Nevertheless, corncobs can be used to provide grain conditioning, hold grain before drying, and level off high humidity peaks when natural grain drying is required.

The natural ventilation system studied is not recommended unless low moisture grain is being conditioned and high wind speeds are available at all times.